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Dendrogeomorphic Analysis of Debris Slides on Mt. Le Conte, Great Smoky Mountains National Park, Tennessee, U.S.A.

Maegen Lee Rochner
University of Tennessee - Knoxville, mneal20@vols.utk.edu

To the Graduate Council:

I am submitting herewith a thesis written by Maegen Lee Rochner entitled "Dendrogeomorphic Analysis of Debris Slides on Mt. Le Conte, Great Smoky Mountains National Park, Tennessee, U.S.A.." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geography.

Henri D. Grissino-Mayer, Major Professor

We have read this thesis and recommend its acceptance:

Sally P. Horn, Carol P. Harden

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

Dendrogeomorphic Analysis of Debris Slides on Mt. Le Conte, Great Smoky Mountains National Park, Tennessee, U.S.A.

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ABSTRACT

Research conducted during the past 30 years tested the use of tree rings to date mass movement events in the mountain areas of Europe and the western and southwestern United States, but few studies have been performed in the eastern U.S., where debris flows, landslides, and rock falls in the Appalachian Mountains pose a common threat to human life and property. One area of particular interest is Great Smoky Mountains National Park (GSMNP). For this study, I tested mature red spruce (*Picea rubens* Sarg.) trees located on or near a debris slide boundary on Mt. Le Conte (LC01) in GSMNP, Tennessee, for a disturbance signal indicative of debris slide events at the site. To first determine if climate influences prevailed at the site and might contribute to abnormal growth patterns, I initially tested sampled trees for climate-growth relationships using DendroClim2002 software. Red spruce on LC01 showed multiple significant climate-growth relationships with monthly and seasonal mean temperature, total precipitation, and PDSI variables. Next, I analyzed suppression and release sequences using a combination of visual and graphical inspection with JOLTS disturbance-detecting software. Detected onset dates identified growth disturbances, but knowledge of significant climate responses in tree growth prompted the use of an ensemble strategy to minimize the influence of the climate signal. I created a difference chronology for analysis in OUTBREAK, compared this with local reference chronologies and with local climate data, and modelled climate using regression residuals in Excel. Combined visual and statistical results provided a list of 20 possible debris slide dates but only three were further supported from results in the ensemble methods: 1909, 1951, and 1981. Results highlighted the importance of the use of an ensemble strategy to better isolate debris slide signals from abnormal growth patterns caused by climate.

In the case of LC01, and perhaps GSMNP, both climate and debris slide signals were present in the tree-ring record, and disturbance detection alone was not adequate for identifying debris slide event years. Climate-growth analysis and subsequent removal of climate signals using a control chronology or other methods should always be an initial step in dendrogeomorphic studies.

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CHAPTER ONE

INTRODUCTION AND QUESTIONS

1.1 Dendrogeomorphology

Tree rings have been used to determine the dates of geomorphic events (McGee 1892; Finch 1937; Lawrence 1946, 1950; Sigafoos 1964; LaMarche 1966, 1968), but Alestalo (1971) is credited with introducing the term "dendrogeomorphology." One set of methods developed by Alestalo focused on changes in annual ring width due to geomorphological changes, while another set focused on secondary succession of trees on newly exposed slopes and deposits left by geomorphic events. Knowing the ages of trees growing on newly exposed slopes or debris deposits can help investigators determine the minimum age of a landslide. Methods of determining mass movement dates are based on the identification of abnormal changes in annual ring width or wood anomaly, scarring, tilting, stem burial, or root exposure. Alestalo (1971) reviewed the literature on dendrogeomorphology and found research to have been concentrated in the western and northwestern portion of the United States (Finch 1937; LaMarche 1968; Lawrence 1946, 1950; Sigafoos and Hendricks 1961). He reviewed the practical purposes of the science for identifying high-risk areas, improving efforts to prevent mass movement, and studying the primary forms of erosion and deposition in different areas.

One of his major contributions to dendrogeomorphology was the connection of ring eccentricity to mass movement events. Ring eccentricity, defined as sustained abnormal increases or decreases in annual ring width, or abnormal growth, is caused by the tilting and survival of affected trees. Alestalo attempted to quantify this eccentricity using the ratio between ring widths in the reaction wood, produced when tilted trees attempt to right themselves, and normal ring widths. The ratio of reaction wood ring width to total diameter growth was used to assign a numerical measurement to ring eccentricity. Determining the onset of ring eccentricity is important for establishing dates of mass movement events. However, ring eccentricity caused by tilting is only one of many forms of evidence found in trees affected by slope failure or instability.

Shroder (1978) further developed the use of ring eccentricity by outlining Process-Event-Response relationships. These relationships describe the processes that affect trees disturbed by mass movements and the ensuing biological responses. Evidence of events includes tree tilting, corrosion, burial, exposure, inundation, and nudation. These processes lead to responses such as formation of reaction wood, scarring, growth suppression and release, ring termination, sprouting, and succession. In his study on the Table Cliffs Plateau in Utah, Shroder (1978) used reaction wood, growth suppression, and scarring in conifers to reconstruct past mass movements. Furthermore, he developed new ways to quantify specific responses, including a new index (I_t). For this index, the sum of event responses per year is divided by the sum of living trees sampled per year and multiplied by 100 to create an I_t index for each year. This adds up the total responses per year but weights them by the number of trees sampled that were living in that year. When I_t values are plotted as a time series event response curve, peaks in index values rising above predetermined minimum index values (dependent on sample size) denote periods of movement.

The study of mass movements has become increasingly important in areas where development encroaches on the natural landscape. Where towns and cities have grown next to unstable slopes, improved understanding of geomorphic processes and frequencies of hazardous events is crucial. Dendrogeomorphology has become a significant part of land-use planning in areas prone to landslides, avalanches, debris flows, mudflows, and other forms of slope failure (Butler *et al*. 1987; Clague 2010; Saez *et al*. 2012; Shroder 1980; Stoffel 2010; Stoffel and Bollschweiler 2008, 2009). By determining frequencies of mass movement events for mountain areas, land management personnel can better design mass movement mitigation and determine development suitability (Clague 2010; Stoffel 2010). One area that would benefit from improved methods for mass movement study is the national park system, where a better understanding of natural hazards is not only prudent for the safety of recreational visitors, but also for the sake of improved understanding of the natural landscapes within different parks. Information about landscapes and different types of mass movements, obtained through dendrogeomorphic methods, extends biophysical data further into the past where aerial photographs, field surveys, and archival records might not reach (Stoffel and Bollschweiler 2008).

Dendrogeomorphic research has provided information on historic mass movement events in the western United States and the mountain regions of Europe, and a few studies have been conducted in the more eroded and less prominent Appalachian Mountains of the eastern United States. Debris flows and landslides in this region pose a common threat and scar the faces and channels of mountains throughout the Appalachian region (Wieczorek and Morgan 2008). In Great Smoky Mountains National Park (GSMNP), landslides, debris flows, and rock falls frequently disrupt transportation routes for hikers and motorists (Henderson 1997). While these natural hazards aggravate and sometimes cause harm, they also provide a prime research opportunity for land managers and scientists who seek to understand the characteristics of local mass movements. Dendrogeomorphology can discover additional landslides and debris flows no longer visually evident or not reported in historical records and contribute to the development of historical mass movement inventories (Stoffel and Bollschweiler 2008). Debris slides are a common feature on the slopes of Mt. Le Conte, GSMNP, but information on their dates of origin and reactivation is incomplete (Henderson 1997). A dendrogeomorphological analysis of debris slides on Mt. Le Conte can provide the missing information needed to complete the record and determine debris slide frequencies.

1.2 Research Design

For this study, I used dendrogeomorphic methods to determine the history of debris slide activations or reactivations on a debris slide scar (Le Conte 01, LC01) on Mt. Le Conte, GSMNP. The study consisted of three main steps, represented by Chapters Three, Four, and Five. Each of these chapters stands alone from the others for possible future publication. The first step (Chapter Three) was to perform an investigative study of the impact of debris slides on trees. I wished to see if I could find evidence in the field that trees on Mt. Le Conte (and perhaps then GSMNP and the southeast) will record debris slide events. I hiked three debris slide scars on Mt. Le Conte, including LC01, and documented (using photographs) visible impacts of debris slides on trees that will be recorded as future evidence of the event. I used the process-event-response relationships defined by Shroder (1978) to outline chapter three.

The next step (Chapter Four) was to determine the influence of climate on red spruce growth and disturbance signals at the study site, LC01. Red spruce (*Picea rubens* Sarg.) was the only species tested because the park restricts the sampling of Fraser Fir (*Abies fraseri* (Pursh.) Poir), and the site LC01 is in the spruce-fir zone. Disturbances at the study site might include climate events such as droughts, so I tested sampled trees for climate-growth relationships and temporal stability prior to dendrogeomorphic analysis. This step also included an examination of the detrending methods used to isolate climate signals. A significant climate influence at the study site (LC01) revealed that climate signals persist despite geomorphic disturbance and prompted additional methods to remove this noise and better isolate a debris slide signal in chapter five.

The final step of this study was to develop a debris slide history for one debris slide scar (LC01) on Mt. Le Conte, GSMNP (Chapter Five). In this step, I first determined possible debris slide dates using visual and statistical analysis of suppression and release sequences seen in tree growth. I then used an ensemble method strategy to isolate growth responses that were most likely caused by debris slides and not climate or some other unknown factor. Some methods and results from Chapter Four are also included in Chapter Five so that Chapter Five can stand alone for possible publication.

1.3 Research Questions

The following research questions, listed by chapter, were addressed in this thesis:

Chapter Three: Feasibility of Dendrogeomorphic Study in the Southeast: A Case Study on Mt. Le Conte, Great Smoky Mountains National Park, Tennessee, U.S.A.

- Can we find evidence in the field that trees in the southeast, and especially GSMNP, will record evidence of debris slide events?

Chapter Four: Analyzing the Impact of Debris Slide Disturbance on the Temporal Stability of Climate-Growth Relationships in Red Spruce, Mt. Le Conte, GSMNP, Tennessee, U.S.A.

- Do significant climate-growth relationships exist between red spruce and monthly climate variables despite the location of the red spruce in a disturbed environment?
- Which detrending method works best for isolating the strongest climate signals in the disturbed environment on Mt. Le Conte?
- Are these climate-growth relationships temporally stable, or do major shifts dominate the signal?

Chapter Five: Dendrogeomorphic Analysis of Debris Slides on Mt. Le Conte, GSMNP, Tennessee, U.S.A

- What are the date(s) of slide activations or reactivations at the debris slide site LC01?
- What are the possible triggers of these debris slides?
- Which forms of tree-ring evidence worked best to identify debris slide dates in GSMNP?

CHAPTER TWO

LITERATURE REVIEW

2.1 Historical Methods and Research

Hupp *et al.* (1987) used tree-ring analysis to determine magnitude-frequency relationships for debris flows on Mount Shasta in northern California. In the case of older debris flow deposits, in which trees surviving the event were no longer available for evidence, Hupp *et al.* used the concept of dendrogeomorphic succession, in which the age of tree cohorts growing on top of the deposit can be used to find the minimum age of that flow, given some lag (or ecesis interval) between deposition and tree germination. They determined that tree groups growing together on greater than 400-year-old debris flow deposits were about the same age, and they used tree cohort age to date debris flows. Using a combination of cohort dating and tree-ring analysis, Hupp *et al.* identified 52 debris flow events on Mt. Shasta, with a mean return interval of 6.24 years. They also identified a cyclic nature of debris flow activity, with periods of high activity clustering together during warmer summers, and developed a frequency-magnitude relationship for both high and low activity periods on the mountain.

Braam *et al.* (1987) took a similar but more quantitative approach to a study of the "Ravin des Aiguettes" and "Pra Bellon" slides in the French Alps. Alestalo (1971) had calculated a measure of eccentricity by dividing the average ring width of the lower side of the trunk (where reaction wood occurred) by the total growth experienced across the full diameter of the tree. Braam *et al.* (1987) took cores at right angles instead. This method accounted for error caused by suppressed growth on the upper side of tilted trees and kept eccentricity from being overestimated. To develop a time series of eccentricity per tree, they plotted eccentricity values for individual dated rings by year. After establishing which trees showed a significant response based on departure from average ring width, a temporal analysis of mass movement per area was performed using the index value developed by Shroder (1978). Years with index values exceeding a set minimum, based on sample size, were marked as event years for an area.

According to Butler *et al.* (1987), minimum index values and minimum sample sizes can be set based on the mass movement studied and the area affected. Because geomorphic processes are not the only factors that affect tree growth, researchers cannot assume that the evidence seen in growth anomalies is always attributed to mass movements. The establishment of adequate sample size and minimum index values can help to reduce undesirable non-geomorphic noise. For example, Shroder (1978) analyzed 250 trees spread over the large area of a slow slide deposit that produced an index value minimum of 4%. Slow mass movements can form large deposits, with smaller portions experiencing movement at different times. This suggests that a small number of trees will be affected by one annual event, making a 4% requirement for significance acceptable (Butler *et al.* 1987). However, snow avalanches affect a high number of trees on isolated paths. Higher index values are more appropriate for snow avalanches because a majority of the sampled trees are affected (Butler *et al.* 1987). For example, Butler and Malanson (1985) established a 40% index value minimum for avalanche paths in Glacier National Park. Their study and the 1978 study by Shroder produced very different index values, so it is unlikely that one minimum index value can be established for dendrogeomorphic purposes. Instead, index values should be determined based on the event or type of movement analyzed. Events affecting smaller areas but more trees are best identified by higher index value minima, and larger areas with fewer trees affected require smaller index values (Butler *et al.* 1987). The researcher must determine what minimum index value works best for every study.

While large sample sizes with appropriately assigned index values will help to reduce the error of misattributing tree-ring evidence to geomorphic processes, a more direct way to reduce error is to better understand how to locate and interpret the evidence itself. Event years are manifested in many different ways: ring anomalies, missing or false rings, abnormally wide or narrow rings and innermost (germination date) and outermost (death/sampling date) rings (Schweingruber *et al.* 1990). Additional evidence of environmental changes includes wood density fluctuations, light rings, reaction wood, callus tissue and traumatic resin ducts, irregular cell formations such as "pith flecks" or tangential discolorations, variation of earlywood vessels in ring porous species, and abrupt growth changes such as very wide or narrow rings seen in growth release and suppression sequences (Schweingruber *et al.* 1990). All of these markers can be used to date many events and environmental changes, not only mass movements, so additional analyses are necessary to attribute markers solely to geomorphic influence. In addition, crossdating is essential, as crossdating with unaffected series (a master chronology) is important for locating false and missing rings and more accurately determining event years (Schweingruber *et al.* 1990).

2.2 Modern Applications of Dendrogeomorphology

Carrara and O'Neill (2003) studied debris flows on the fault-ridden slopes of the Gravelly Range in Montana and used evidence of growth reductions and reaction wood to reconstruct event frequencies. The marked growth reduction was any reduction where a ring was equal to or less than 50% the width of the preceding ring. Cores taken to obtain reaction wood came from trees tilted 10–80 degrees at a height of 30 cm from the ground. Reaction wood was identified as darker wood with thicker cells and rounder tracheids. In most cases, the beginning of reaction wood growth is close to the tilting year, but in some it can be delayed by a recovery period of narrow ring growth. Carrara and O'Neill collected cores and cross sections from conifers found at three sites in the Gravelly Range: Bench Road, Cliff Lake, and Freezeout Lake. They plotted the percentage of trees disturbed in a given year per site. Disturbance cases below 30% recorded per year were disregarded as "noise," or possibly as having been caused by other environmental factors. Some peaks in disturbance cases, however, were well above 40–60%: Bench Road had six episodes of mass movement, Cliff Lake six, and Freezeout Lake eight.

Some of the event years identified by Carrara and O'Neill corresponded with years of known earthquakes: three of six at Bench Road, two of six at Cliff Lake, and four of eight at Freezeout Lake. Carrara and O'Neill claimed that earthquakes were the most likely cause of landslides because of evidence of known earthquake-landslide relationships in the Intermountain Seismic Belt (most notably the Hebgen Lake Earthquake and the subsequent Madison River landslide at Rock Creek Campground). Carrara and O'Neill used the results of Keefer (1984) to determine how close an earthquake epicenter had to be to their site to likely trigger an earthquake. According to Keefer (1984), an earthquake with a magnitude of 6.0 could cause a landslide within 40 km of its epicenter (Keefer 1984). Eight earthquakes with magnitudes of more than 6.0 had been recorded within 200 km of the sites studied by Carrara and O'Neill (2003). If landslides were indeed caused by earthquakes more than 40 km away, it is possible that different factors of earthquake dynamics can cause landslides to occur further from earthquake epicenters than previously estimated, leaving room for further study in earthquake-landslide relationships (Carrara and O'Neill 2003).

Stem tilting and growth suppression were also used as tree-ring evidence of debris slides by Fantucci and Sorriso-Valvo (1999) in their study of white oaks and black pines on a mass movement complex near Lago, Calabria, Italy. To help identify tree-ring evidence associated with mass movement events, growth patterns from affected trees were compared with those from unaffected trees. If a release or suppression seen in trees affected by mass movement was also seen in unaffected trees, the mass movement could not have caused the growth change. An "anomaly index," calculated through a combination of three factors (rings showing suppression, the magnitude of the suppression, and the total sample count), was used to identify periods of disturbance (Fantucci and Sorriso-Valvo 1999). The anomaly index was calculated using the sum of trees showing suppression for a given year, multiplied by a weight of 1–4 based on the intensity of the suppression, and divided by the number of trees alive in that year at the site. In some cases, disturbance years correlated with years that also recorded increased precipitation and earthquakes, linking periods of increased landslide occurrence with possible triggers. Using historical records of mass movement dating back to the 1850s, Fantucci and Sorriso-Valvo (1999) attempted to link landslides and tree growth suppression to earthquakes and other possible causes. Where peaks in the disturbance plot matched recorded events, they tentatively linked landslides and precipitation or earthquake data. Even though they could not firmly establish the causal relationships, the findings suggested room for future study combining dendrogeomorphic determination of event dates with attempts to identify possible triggers.

Saez *et al*. (2012) also attempted to link landslides with their triggers when dating landslide reactivations on the Bois Noir, French Alps, an area characterized by fractured geology and intense summer storms. They focused on tilted and *s*-shaped stems, scars, breakages, and growth suppression. In the affected trees, Saez *et al.* (2012) assessed both reaction wood formation and any marked growth reductions lasting five or more years with at least 50% decrease in ring width. These growth reductions were plotted using the I_t index (Shroder 1978) to determine disturbance by year. Reaction wood was used, based on its location in the early portion of the earlywood, late portion of the earlywood, or in the latewood, to determine approximate seasonality of the landslide within a ring year. Saez *et al*. concluded that the largest landslides occurred between October and April 1946–1947, October and April 1992–1993, and July and September in 1977 and 2000. The landslides noted in the study did not all coincide with periods of unusually high amounts of summer precipitation, but landslide probabilities increased when periods of July-August rainfall were greater than 200 mm. Saez *et al*. were able to distinguish eight different landslide events, both adding to and reconfirming archival data on historical events, while also linking 50% of these events with periods of high July-August rainfall. Using reaction wood positions within annual rings allowed for seasonal accuracy in distinguishing the timing of debris slide events, further supported by historic data and aerial photos.

Many dendrogeomorphological mass movement analyses evaluated precipitation records to determine possible slide triggers, but Bollschweiler and Stoffel (2010) attempted to determine if changes in debris flow trends and frequencies might be related to long-term climate changes. Using tree-ring data from 2,467 conifers on eight different debris flow paths in the Zermatt Valley, Swiss Alps, they analyzed both short-term and long-term changes in climate to determine which exert more influence on debris flow frequency. Debris flows in the Alps are usually triggered by convective thunderstorms or advective rainfall events, but this hydroclimatic control of rainfall events could be affected by changing climate, especially current global warming, if climate changes lead to increases or decreases in the frequency of rainfall events. Using growth anomalies in conifers, Bollschweiler and Stoffel (2010) were able to reconstruct 417 debris flow events that occurred between 1600 and 2009. While most dendrogeomorphic studies of debris flows have been restricted by smaller data sets covering one path over a short period, the conifer series used by Bollschweiler and Stoffel were unique in that they covered eight paths in the Zermatt Valley that had occurred over many decades. This allowed for a regional-scale study across multiple small valleys. Event years that affected at least 50% of the eight torrents were considered valley-wide events. Overall, low rates of debris flow activity were noted during the 19th century and the most recent decade of 2000–2009. High rates of activity were noted in the early 20th century (1920–1929) and late 20th century (1990–1999), and coincided with warm, wet periods, especially after the Little Ice Age. Cooler temperatures during the Little Ice Age and at other times helped stabilize the permafrost environments and control the mobilization and size of debris flows. Warm and wet environments, with a higher range in daytime temperatures, led to freeze/thaw cycles that helped to provide sediment and mobilize debris flows. Bollschweiler and Stoffel (2010) concluded that relationships existed between long-term climate changes and debris flow frequencies in the past, but that the influence of future climate change remains unclear.

Conifers are the dominant tree species used in dendrogeomorphology, mainly because they dominate high mountain areas where mass movements most frequently occur, they tend to live longer, and they are easier to work with. Arbellay *et al.* (2010) attempted something new and analyzed only broad-leaved trees to reconstruct debris flow activity in the Illgraben Torrent of the Swiss Alps. Arbellay *et al.* (2010) used species of alder, poplar, aspen, birch, and willow. Their reconstruction used injuries and growth anomalies instead of reaction wood to indicate mass movement events because of the tendency of these hardwood trees to bend toward sunlight. An abrupt growth change was defined as one lasting at least two years and showing a 66.6% growth reduction or 300% growth increase (strong), or a 50% growth decrease or 200% growth increase (weak). In some cases, events were dated to the season, using positions in the early earlywood, late earlywood, or latewood. A total of 444 growth disturbances, most from injury and growth suppression, were noted, allowing the reconstruction of 14 debris flow events from 1965 to 2007. Archival records had recorded only 15 debris flows overtopping channel banks (and affecting trees) from 1793 to 2005, a largely underestimated value based on the 14 events identified by Arbellay *et al*. during the shorter period of 1965–2007.

2.3 Debris Flow Research in the Eastern U.S.

While dendrogeomorphic research has been common in the western and southwestern United States, very few studies have been performed using dendrogeomorphic methods in the Appalachian Mountains of the eastern United States. Studies of vegetation recovery on debris slide scars have been more common in different regions of the Appalachian Mountain chain. Flaccus (1959) studied landslides in the White Mountains of New Hampshire, noting the speed of revegetation and the first species to grow back on five different slides. The study used density, frequency, and dominance of different tree species on landslide areas to determine patterns of revegetation. However, his dating relied mostly on known dated and documented slides and involved no tree-ring analysis. The four dominant pioneer tree species were paper and yellow birch (*Betula alleghaniensis* Britt.), quaking aspen (*Populus tremuloides* Michx.), and pin cherry (*Prunus pensylvanica* L.f.). According to Flaccus (1959), bare rock and talus at high elevation sites of disturbance can remain bare for up to 100 years and are the slowest to recover through secondary succession. However, on lower elevation slopes that are less steep, some seeds and organic material from plants remain in areas of slide deposition. These areas show more rapid revegetation of hardwood species. Spruce and fir trees eventually dominate at high elevation sites and grow to become the dominant canopy tree as hardwoods phase out. However, spruce and fir trees are slowest to recover from landslide disturbance (Flaccus 1959). These findings were important to botanical studies, but did not use dendrogeomorphology to reconstruct slide dates.

Hull and Scott (1982) studied slide revegetation on debris avalanches in Virginia. They focused on events following Hurricane Camille (August 19–20, 1969) and the rates of vegetation recovery afterwards. Like Flaccus (1959), Hull and Scott also focused on the density and frequency of plant species, including not only trees, but also vines, shrubs, and other plants. They were able to identify differences between trees on disturbed and undisturbed slopes and to determine which species were likely to contribute to site recovery at different debris avalanche sites. A mixture of species from the surrounding mature forest and new successional species was found on deposits, but much depended on the size of the debris avalanche and which species were available to contribute seeds to microsites, or pockets of soil. Hull and Scott (1982) found that the main factors that controlled revegetation following debris avalanches were the species surrounding slides in the undisturbed forest and the amount of soil removed by the slide. Like Flaccus, Hull and Scott (1982) focused on which species were likely to take over on exposed slopes and did not use dendrogeomorphology.

In contrast, Hupp (1983) applied dendrochronological techniques to better understand the temporal and spatial extent of mass movements in Virginia block fields. He studied scarring and tilting in more than 200 trees obviously affected by mass wasting. Tree-ring analysis was used in addition to lichen analysis and block weathering measurements to date 13 mass movements between 1889 and 1979. Even though the block fields were likely formed during the Pleistocene, research performed by Hupp showed recent movement of them, primarily during high rainfall events. Such events increase pore water pressure between rocks and also cause water to flow on shale layers beneath the block fields, eventually causing slope failure. Dendrogeomorphic evidence helped to determine dates of movement and determined that mass wasting of the block fields was the primary erosion process shaping slopes in the area.

Eshner and Patric (1982) collected reports of debris avalanches after high rainfall events in the northern, central, and southern Appalachian Mountains. The goal of the study was to review research and data on mass movement events in the mountain areas of the eastern United States and to propose possible relationships between mass movements, rainfall, and erosion, based on what they found during the review. Similar to the findings of Hupp (1983), they determined that increased pore water pressure in soils and widening of flow layers between soil and impermeable layers, especially during high intensity storms (100-year events), to be the primary causes of debris avalanches in the Appalachian Mountains. Eshner and Patric determined that five inches of rain (12.5 cm) was sufficient to saturate soil and increase the risk of debris slides. Debris slides are most likely to occur on steep slopes (25 to 40 degrees) underlain by impermeable rock and covered with only thin soil. Another example of this arrangement occurs in the Anakeesta Formation on steep slopes of high elevation peaks in GSMNP.

Eshner and Patric (1982) called debris slides an unavoidable "act of god." However, land owners and managers can prepare for such events through improved data on the frequency and extent of mass movement in mountain areas. Data on past movement would help determine areas of high susceptibility and the appropriate mitigation efforts to predict, prevent, or protect from dangerous slide occurrences. A dendrogeomorphological analysis of debris slides on Mt. Le Conte, GSMNP, would contribute to this effort by providing data on when major debris slides occurred on the mountain, and would support future use of the science for dating debris slides elsewhere in the park.

2.4 Debris Flow Research in the Great Smoky Mountains

Previous research on mass movements in GSMNP has demonstrated the potential of dendrogeomorphic studies in the park. Bogucki (1970) identified 100 debris slide events resulting from a September 1, 1951 cloudburst. Forty-one of the 100 slides occurred in the Alum Cave Creek watershed of Mt. Le Conte. Bogucki (1970) used field surveys and aerial photos to locate slide scars and stressed the need to better investigate slide damage and debris flow events in the southern Appalachians. In a later study, Bogucki (1976) continued his work on the debris slides of Mt. Le Conte and noted slide damage to roads and trails in the park, especially along the Alum Cave Bluffs Trail to the peak of Mt. Le Conte. In both studies, Bogucki emphasized the importance of dating past debris slides to determine areas of high risk and to identify areas of potential activity. In addition to these conclusions, Bogucki provided maps of the 1951 slides, especially those that occurred in the most accessible areas along the Alum Cave Bluffs trail. These maps proved valuable for identifying slide scars on Mt. Le Conte and for performing dendrogeomorphic analysis, as surviving trees should still mark the 1951 event.

Clark (1987) also studied Appalachian slope processes and compiled 51 mass movement triggering events between 1844 and 1985, including the cloudburst leading to the 1951 events on Mt. Le Conte studied by Bogucki (1970). Clark stressed the need for more research to determine debris flow triggers in the Appalachians and noted that high rainfall events were likely the primary contributing factor. Clark *et al.* (1987) also stressed the need for more study at the local level because isolated summer rain events have often been noted before debris flow events on Anakeesta Ridge in the GSMNP. Precipitation data, in addition to data on soil type, moisture, vegetation, and land use, would benefit attempts to predict areas of future slope failure, especially in light of increasing misuse of land by people living in mass movement prone zones. Improved dating techniques, such as dendrogeomorphology, could extend data for mass movement frequencies and improve attempts to predict hazardous areas before people build on them.

Ryan (1989) worked on debris flows on Anakeesta Ridge and was the first to incorporate dendrochronology into his study of mass movements in that area. The tree-ring analysis yielded a frequency range of one debris flow event every six to 87 years with an average return interval of 13.8 years. Using the ages of new forest stands growing on surfaces exposed by past debris flows, Ryan determined minimum dates for flows ranging from 1749 to 1971. Only minimum dates could be estimated, because Ryan had no data on the lag time between slide events and reestablishment of vegetation on slide scars. The age of new forest stands on debris deposits or slide scars allowed him to estimate that slide events were at least as old as the forest stands but likely older due to unknown lag times. Ryan associated mass movement events with periods between high precipitation events but also with periods of landscape "ripening," which alternate with times of "flushing." Ripe slopes are highly weathered and hold a collection of regolith material waiting to be flushed away by a precipitation event downslope in a debris slide. By locating "ripe" slopes and calculating debris slide frequency for disturbed slopes, researchers can better delineate high risk areas.

One such study was completed by Henderson (1997) on Mt. Le Conte. He was the first to map debris slide susceptibility in GSMNP. Using a combination of GIS and spatial statistics, he attempted to discover the primary driving factors behind mass movement events on Mt. Le Conte, and he extended the debris slide inventory presented by Clark (1987). He listed 10 main debris slide events between 1942 and 1995 on Mt. Le Conte, Anakeesta Ridge, and Newfound Gap. The list included five events from Clark (1987) that occurred prior to 1984, but Henderson expanded the debris slide inventory into 1995 with two events, one following a cloudburst on Mt. Le Conte on June 28, 1993, and one during Hurricane Opal on October 4–6, 1995. Like many other researchers in the park, Henderson expressed the need for debris and landslide inventories and delineated high-risk areas. These areas identified by Henderson included south slopes (corresponding with prevailing dip in the same direction), areas receiving the highest annual precipitation, those underlain by the Anakeesta formation, hollows frequented by debris flows but likely originated by wedge failure, and areas with slope angles between 30 and 50 degrees. The existence of areas with combinations of these characteristics makes forecasting slope failure extremely difficult, but mapping areas where mass movements have occurred, and are likely to occur in the future, is necessary when development continues to occur in mountainous areas. Even though GSMNP is a natural landscape, outside the development of park facilities, roads, and trails, improved mapping of susceptible areas would aid in the maintenance of these facilities and improved safety for recreational visitors in the park. Tree-ring evidence of debris slide susceptibility could be a major part of identifying the most highly susceptible areas. However, of the GSMNP debris slide studies reviewed for this thesis, the study by Henderson (1997) was the only one to use dendrochronology.

CHAPTER THREE

Feasibility of Dendrogeomorphic Study in the Southeast: A Case Study on Mt. Le Conte, Great Smoky Mountains National Park, Tennessee, U.S.A.

This chapter is intended for publication in the journal *The Geographical Bulletin*. I developed the research topic with my advisor and second author, Dr. Henri Grissino-Mayer. The use of "we" within the text refers to me and Dr. Grissino-Mayer, who assisted with project development, site selection, field collection, and text editing. My contributions to this chapter include field collection, interpretation and graphic displays of results, and writing the manuscript.

3.1 Abstract

Dendrogeomorphic analysis of debris slides has been common in the western and southwestern United States, but is less common in the eastern U.S. and especially in Great Smoky Mountains National Park (GSMNP). The goal of this study was to determine if southeastern tree species in GSMNP can record evidence of debris slides in the tree-ring record. We specifically sought evidence in the field that trees along debris slide scars on Mt. Le Conte (and perhaps then GSMNP and the southeastern U.S. in general) will record debris slide events. Several debris slide scars on Mt. Le Conte were scouted for visual evidence of the impact of a debris slide on trees: LC01 at N 35.65100 W 83.44100 (approximately 1800 m elevation), SB-8 (a 1951 cloudburst slide) at N 35.65147 W 83.43591 (approximately 1800 m elevation), and LC02 (a recent slide from approximately August 2012) at N 35.63928 W 83.44772 (approximately 1500 m elevation). We documented visible impacts of debris slides on trees that could serve as future evidence of the event. We used the process-event-response relationships defined by Shroder (1978) to outline the evidence found. The identification of visible debris slide impacts to trees known to leave evidence in the tree-ring record served as confirmation of current and future use of dendrogeomorphic methods on Mt. Le Conte and in GSMNP.

3.2 Introduction

Shroder (1978) outlined the impacts of geomorphic events on trees and their subsequent responses (Table 3.1). Process-Event-Response relationships describe the sequence of events and evidence left behind in the tree-ring record. The process is the geomorphic incident that leads to an “event” in the tree. The “event” describes what happens to the tree as a consequence of the geomorphic occurrence, such as: tree tilting, corrosion, burial, exposure, inundation, and nudation. The response describes the biological response of the tree to the event, such as: scarring, growth suppression or release, ring termination, sprouting, and formation of reaction wood. Secondary succession can also occur when trees reestablish on exposed slopes and debris slide deposits. The inner ring dates of these trees can be used to help estimate the date of the debris slide (Shroder 1978). For this study, we identified external signs of events (in this case resulting from debris slides) to infer likely future internal, tree-ring evidence of these events in the trees as a result of the subsequent biological response.

For the purposes of this study, the term “debris slide” is a hybridization of a debris flow and a translational landslide. It is defined by Easterbrook (1999) as the “rapid downward movement of predominantly unconsolidated and incoherent debris in which the mass does not show backward rotation but slides or rolls forward, forming an irregular hummocky deposit.” Debris slides are most common in mountainous areas where thin layers of sediment collect on top of tilted bedrock layers. Heavy rainfall often leads to saturation of these thin layers, which can break loose and slide as masses of unconsolidated sediment and rock over the top of the planar bedrock surfaces (Easterbrook 1999) (Fig. 3.1). Debris slides are a common natural disturbance on Mt. Le Conte in GSMNP, where thin soil layers underlain by tilted Anakeesta

Table 3.1: Outline of debris slide effects and the resulting evidence recorded in the tree-ring record, based on Shroder (1978).

Debris Slides and The Effects on Trees	
Impact	**Evidence**
Injury, Removal or Damage to Roots,	Suppressed Growth
Removal or Damage to Crown	
Removal of Competition	Release in Growth
Injury	Scarring
Tree Tilting	Compression Wood Growth (Conifers) Tension Wood Growth (Hardwoods)
Tree Death	Death Dates = Event Date
Land Clearing or Deposition	Secondary Succession = Reestablishment of Tree Species

Formation layers are prone to sliding after heavy rainfall (Hadley and Goldsmith 1963; Moore 1988; Henderson 1997). We chose Mt. Le Conte as the study site for this study because of the high number of visible debris slide scars and efficient access to these scars from trails, roads, and streams in GSMNP.

Because of the lack of dendrogeomorphic studies in the eastern United States and particularly in GSMNP, confirmation of the ability of trees to record a debris slide signal is needed before dendrogeomorphic analysis can be performed in GSMNP. An exploration of the impacts of debris slides on trees in GSMNP was needed to better associate internal tree-ring evidence with external signs of debris slide disturbance in trees. Even though Henderson (1997) performed a dendrogeomorphic analysis in his study of debris slide susceptibility in the Mt. Le Conte-Newfound Gap area of GSMNP, the focus was on the secondary succession of trees on slide deposits and not on the possible internal recording of events. The goals of this study were to document the impact of debris slides on Mt. Le Conte trees and better understand what to look for when identifying trees most likely to have recorded debris slide events in their tree-rings. Our overarching goal was to determine if a dendrogeomorphic study was feasible in GSMNP and in turn the southeastern U.S.

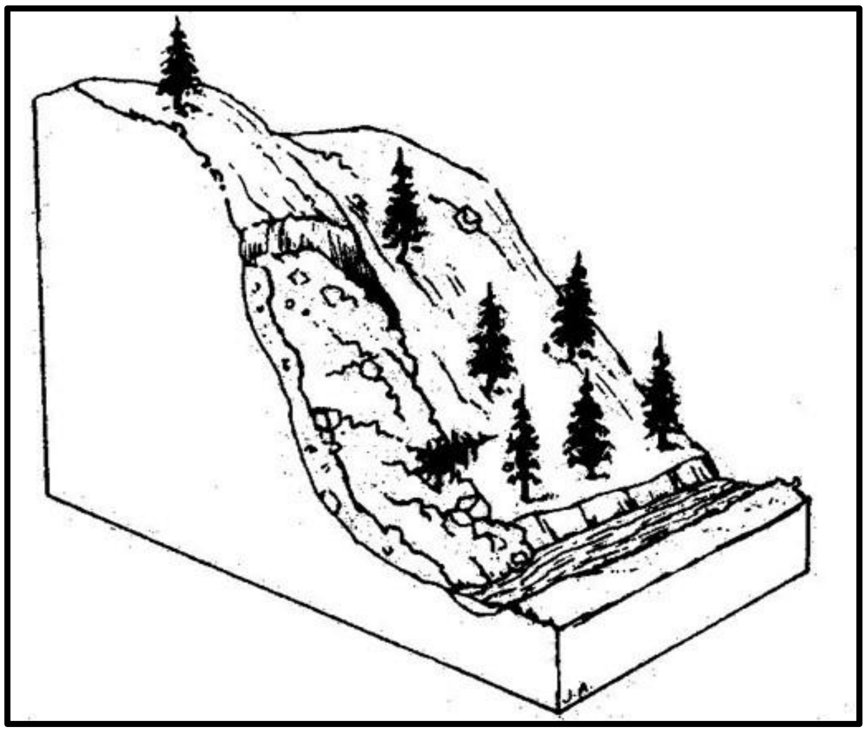


Figure 3.1: Debris slide diagram
provided by Appleby, R. Kilbourne, and C. Wills after Varnes (1978)
http://www.consrv.ca.gov/cgs/geologic_hazards/landslides/Pages/Index.aspx

3.3 Study Site

We chose to investigate three debris slide scars on Mt. Le Conte, Great Smoky Mountains National Park (GSMNP), for visual evidence of the impact of a debris slide on trees: LC01 at N 35.65100 W 83.44100 (approximately 1800 m elevation), SB-8 (a 1951 cloudburst slide studied by Bogucki 1970) at N 35.65147 W 83.43591 (approximately 1800 m elevation), and LC02 (a recent slide from approximately August 2012) at N 35.63928 W 83.44772 (approximately 1500 m elevation). LC01 is a debris slide complex that consists of three slide areas joined at the base and bisects the Alum Cave Bluffs Trail in GSMNP about 6.5 km from the trailhead at Hwy 441. The slide scar drains into the Trout Branch in GSMNP. LC01 is the shortest of the three slides investigated at only about 0.20 km long from the highest point to where it becomes less prominent in a narrow drainage. LC01 is on the rust-stained Anakeesta Formation, which includes metasiltstone, phyllite, slate, metasandstone, schist, and dolomite (Hadley and Goldsmith 1963). The tilted layers of this formation lead to thin soil layers and frequent debris and landslides in GSMNP (Hadley and Goldsmith 1963; Moore 1988; Henderson 1997). Because of the high elevation at LC01, red spruce (*Picea rubens* Sarg.) and Fraser fir (*Abies fraseri* (Pursh) Poir) are the dominant tree species along the edges of the slide scar.

The slide scar SB-8 (Bogucki 1970), like LC01, is also at high elevation and is underlain by the Anakeesta Formation. The head of the SB-8 slide scar is located at N 35.652457 W 83.436154, approximately 1882 m elevation, and it stretches approximately 0.40 km downslope until in joins the chute of another documented 1951 slide, SB-10 (Bogucki 1970). Both SB-8 and SB-10 drain into the Styx Branch in GSMNP. We accessed this slide from the switchback with stairs on the Alum Cave Bluffs Trail approximately 6 km up from Hwy 441 (N 35.650362 W 83.435419). Like at LC01, spruce and fir dominate the perimeters of the slide scar.

The final slide scar we investigated, LC02, lies at a much lower elevation, but is the longest and most recent slide of the three studied. Bedrock exposed on LC02 consists of Anakeesta slate and phyllite and Thunderhead sandstone. Estimated to have occurred around August 2012, LC02 is approximately 1.6 km long from head to base, where it intersects Trout Branch at N 35.637140 W 83.454513, approximately 1235 m elevation. The slide head is visible from the Alum Cave Bluffs Trail about 3.6 km up from Hwy 441 and lies only about 5 m downslope from the trail. Unlike LC01 and SB-8, LC02 is at a lower elevation, and an abundance of tree species dominate along the perimeter of the slide scar. Some of the most common include: yellow birch (*Betula alleghaniensis* Britton), American beech (*Fagus grandifolia* Ehrh.), yellow poplar (*Liriodendron tulipifera* L.), red oak (*Quercus rubra* L.), white oak (*Quercus alba* L.), yellow buckeye (*Aesculus flava* Sol.), sugar maple (*Acer saccharum* Marsh), and red maple (*Acer rubrum* L.). At the higher elevations of LC02, red spruce trees are more abundant. We accessed LC02 via the Trout Branch which is accessible where it flows under Hwy 441 in GSMNP at N 35.634512 W 83.461199, at approximately 1132 m elevation. The debris ball of LC02 lies about 0.80 km up Trout Branch from the highway.

3.4 Methods

To obtain visual evidence of the impact of debris slides on trees of Mt. Le Conte, we hiked the three debris slide scars (LC01, LC02, and SB-8) and took photographs of known debris slide “events” (Shroder 1978) in trees bordering and near to (within 5 m) the debris slide scars.

We photographed evidence of injury, removal of roots, damage to the crown, scarring, tilting, secondary succession, and trees killed by the debris slide both on the perimeter of the slide and preserved within debris or log jams along and at the bottom of the debris slide. We used the process-event-response sequence outlined by Shroder (1978) to organize results, which consisted of the visual evidence of debris slides seen in trees on Mt. Le Conte. Ultimately, this paper serves as a summary of the evidence preserved in the tree-ring record needed to perform a dendrogeomorphic study, illustrated with photographs that confirm the feasibility of finding this evidence in GSMNP and possibly the southeastern U.S.

3.5 Results: Evidence of Debris Slide Occurrence in Trees

3.5.1 Suppression and Release Sequences

One form of evidence used in dendrogeomorphic study is the identification of suppression and release sequences. A suppression sequence is a period of years with drastically reduced growth, as much as a 200% reduction (Schweingruber 1990; Carrara and O'Neill 2003; Arbellay *et al*. 2010; Clague 2010; Saez *et al*. 2012), following injury, damage to the crown, or exposure of roots (Fig. 3.2) caused by a debris slide. A release sequence is a period of years with increased growth, as much as a 200% increase (Schweingruber 1990; Carrara and O'Neill 2003; Arbellay *et al.* 2010; Clague 2010; Saez *et al*. 2012), following the removal of competition by a debris slide. Both occur abruptly, without a gradual transition, as seen in the example core collected from LC01 (Fig. 3.3) (Schweingruber 1990; Carrara and O'Neill 2003; Arbellay *et al.* 2010; Clague 2010; Saez *et al*. 2012). Trees most likely to have experienced suppression, release, or both are located on or near the perimeter of a debris slide scar, such as seen at LC02 (Fig. 3.4). Trees that are on the perimeter but have not been injured will experience growth release. In some cases, a tree can be injured, causing suppression, but after recovery can experience reduced competition and then experience a growth release (Schweingruber 1990; Carrara and O'Neill 2003; Arbellay *et al.* 2010; Clague 2010; Saez *et al*. 2012). Even if trees are meters away from the slide scar, they can still show release after removal of nearby competition, or suppression following injury or exposure of roots that extended laterally into slide areas. We observed examples of lateral extension of roots into slide areas at LC01 (Fig. 3.5).

Figure 3.2: Red spruce on the perimeter of slide LC02 with exposed roots and injury, including that caused by a debris dam pushed against it (Photo by Maegen Rochner).

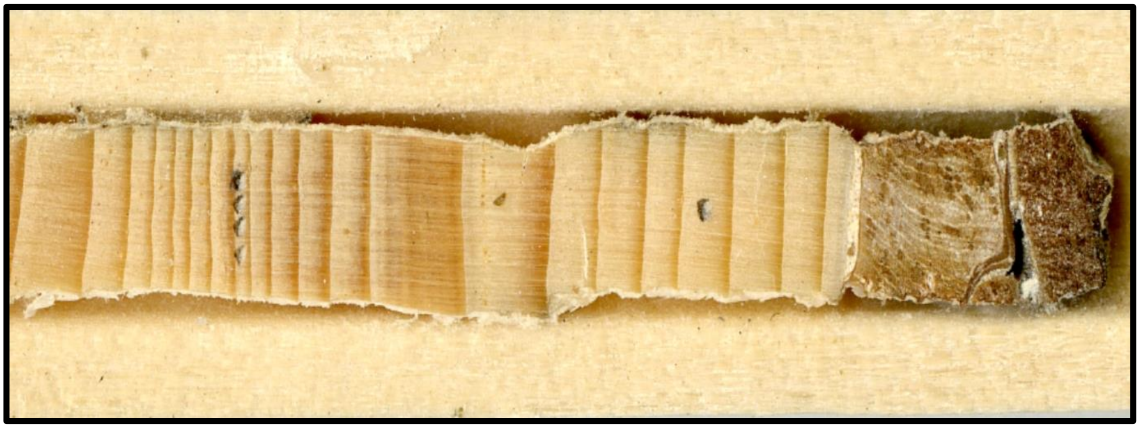


Figure 3.3: Red spruce core collected from LC01 showing suppression in 1995/1996 and release in 2005/2006. Four dots on a ring mark the year 2000, and a single dot marks a decade ring, in this case 2010.

3.5.2 Scarring and Injury

Slide perimeter trees might also possess scars that indicate injury. Just as fire scars can pinpoint the year of a fire (Grissino-Mayer 1995), scars due to injury from falling or sliding debris can be dated to determine an event year. In some cases, scars from a past debris slide are still visible (Fig. 3.6) and sampling can recover this evidence, but in many, scars from past events are buried within the tree. These buried scars can only be found by taking cross-sections or by chance obtaining one with an increment borer. In those cases where scars or other anomalies are apparent, coring is best performed according to the relative location of the anomaly on the trunk (Stoffel and Bollschweiler 2008). Cores are extracted from two locations on the tree: one from opposite and another adjacent to the wound (Fig. 3.7). Cores taken directly from the scar or within the callus tissue will not contain all the rings of the tree due to irregular ring formation as the tree heals. The core taken adjacent to the scar must be close

Figure 3.4: Debris slide scar at LC02. Trees on the perimeter of the slide scar will be most likely to record the event in their rings because they are near enough to have been affected by the slide or to have experienced a decrease in competition (Photo by Maegen Rochner).

Figure 3.5: Red spruce at LC01 with roots extending laterally into the main slide scar (Photo by Maegen Rochner).

Figure 3.6: Injured and scarred tree adjacent to LC02 (Photo by Maegen Rochner).

Figure 3.7: Co-author Dr. Henri Grissino-Mayer collects a core adjacent to a scar in a red spruce tree at LC01 (Photo by Maegen Rochner).

enough to obtain evidence of the callus tissue and perhaps traumatic resin duct formation (Stoffel and Bollschweiler 2008).

3.5.3 Tilting and Compression Wood

Debris sliding downslope can act as a bulldozer, injuring trees and tilting them in the direction of flow. Tilting is most common at the base of a slide, at the debris ball (Fig. 3.8), but can also form where debris is jammed up against the trunk of a tree in a debris dam (Fig. 3.9). Trees that survive tilting return to a more upright position by forming reaction wood: compression wood on the downhill side of gymnosperms (conifers) and tension wood on the uphill side of angiosperms (hardwoods) (Stoffel and Bollschweiler 2008). In most cases, the beginning of reaction wood growth occurs close to the tilting year, but in some, it can be delayed by a recovery period characterized by narrow ring growth (Carrara and O'Neill 2003).

In the case of tilted trees, at least two cores need to be taken. To capture reaction wood growth in coniferous trees, cores must be taken from the downhill side of the tree at ground level, and in deciduous trees must be taken from the uphill side of the tree at ground level (Stoffel and Bollschweiler 2008). Ring eccentricity can then be calculated by the ratio of normal growth (from cores taken at right angles to reaction wood) and abnormal growth on the uphill or downhill side of the trunk (Braam *et al*. 1987; Alestalo 1971).

Figure 3.8: Tilted tree at the debris ball of LC02 (Photo by Maegen Rochner).

Figure 3.9: Trees tilted and killed by debris damming near the base of LC02 (Photo by Maegen Rochner).

3.5.4 Death Dates and Succession

In addition to mature red spruce trees on the perimeter of the slide (with evidence of suppression or release, scarring, or tilting) younger trees that represent vegetative regeneration on old slide scars are also useful in a dendrogeomorphic study (Fig. 3.10). Trees with normal growth curves and no growth aberrations germinated after the debris flow event. This provides supplemental evidence for estimating the date of the slide. Secondary succession occurs as a response to removal of surface material, as land stripped clean by mass movement events allows growth of a new forest cohort where soil material has collected on exposed surfaces. Dating secondary succession of trees provides estimates of minimum event ages, but regeneration rates can vary depending on microclimate and habitat factors or lag time between the mass movement event and plant establishment (Shroder 1980; Hupp *et al*. 1987; Stoffel and Bollschweiler 2008, 2009; Clague 2010). On the higher elevations of Mt. Le Conte, climate and geologic conditions slow the re-establishment of Fraser fir (*Abies fraseri* (Pursh.) Poir) and red spruce (*Picea rubens* Sarg.) (Flaccus 1959; Pauley 1993; Wise and Petersen 1998). On the debris slide scar of LC01, we found that Fraser firs have so far been the first to regenerate (Fig. 3.11) and did not observe any spruce saplings at the site.

Trees killed by a debris slide, either by removal or by injury, can also provide evidence of the debris slide event (Fig. 3.12). The death dates of these trees will be equal to the date of the debris slide unless a lag time exists between injury and death. Preserved logs found in a slide debris ball, like that seen at LC02 (Fig. 3.13) or in debris dams (Fig. 3.14) can provide death dates, as long as they remain well-preserved. However, the chronologies provided by such trees are floating, and must be crossdated with other living chronologies. To use the age defined by the rings of the tree to date the event requires the assumption that the landslide killed the tree within the final growth year. If bark is preserved, this assumption holds better than with other pieces of debris because woody debris on the forest floor that could be derived from long-dead material could have been carried by the slide. Because of such complications, dendrochronology works best if multiple methods are applied to dating debris flows or other mass movements (Clague 2010).

3.6 Conclusions

Despite the absence of dendrogeomorphic studies performed in GSMNP and the Appalachian Mountains of eastern North America, trees have the potential to record evidence of debris slides in the tree-ring record. During exploration of three debris slide scars on Mt. Le Conte in GSMNP, multiple events (Shroder 1978) were identified that affected trees and will, or have already been, recorded by the trees for future study. We found all of the forms of evidence outlined by Shroder (1978) on Mt. Le Conte in GSMNP. However, the type of evidence used during dendrogeomorphic study will depend on the researcher and the location studied. For example, an area on a steep slope, where trees tilt and produce reaction wood naturally, would make it more difficult to determine which were tilted by debris (if the debris is no longer evident) and which were tilted by downslope movement.

The identification of apparent debris slide influence on trees and external events known to induce internal responses (Shroder 1978) in trees makes the application of dendrogeomorphic methods valid in GSMNP. The likelihood is also high that dendrogeomorphology is a feasible approach for helping answer geomorphic questions in the southeastern U.S. The capacity for tree-ring reconstruction of past debris slide events exists in GSMNP and opens doors for future work in the park and perhaps elsewhere in the Appalachian Mountains and the southeastern U.S.

Figure 3.10: Red spruce regeneration at LC02 (Photo by Maegen Rochner).

Figure 3.11: Fraser fir regeneration on the slide scar head above Alum Cave Bluffs trail at LC01 (Photo by Maegen Rochner).

Figure 3.12: Pile of plant debris in the slide scar of SB-8. The death dates of downed trees can help provide approximate dates of the debris slide (Photo by Maegen Rochner).

Figure 3.13: Debris ball at the base of LC02 with author, Maegen Rochner, for scale (Photo by Chris Rochner).

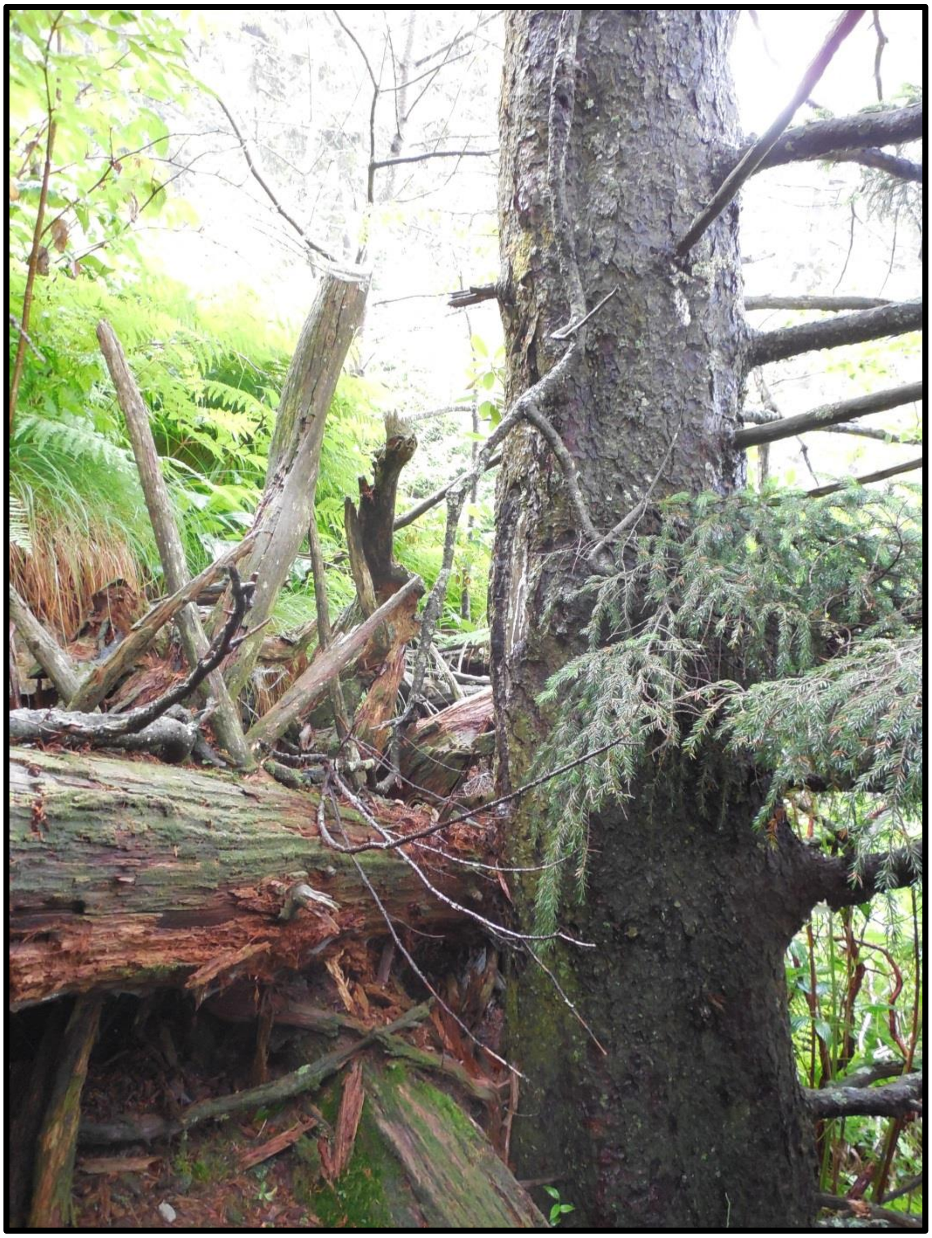


Figure 3.14: Debris dam on a red spruce at LC01 (Photo by Maegen Rochner).

CHAPTER FOUR

Analyzing the Impact of Debris Slide Disturbance on the Temporal Stability of Climate-Growth Relationships in Red Spruce, Mt. Le Conte, Great Smoky Mountains National Park, Tennessee, U.S.A.

This chapter is intended for publication in the journal *Tree-Ring Research*. I developed the research topic with my advisor and second author, Dr. Henri Grissino-Mayer. The use of "we" within the text refers to me and Dr. Grissino-Mayer, who assisted with project development, site selection, field collection, and text editing. My contributions to this chapter include field collection, processing and dating of samples, data analysis, interpretation and graphic displays of results, and writing the manuscript.

4.1 Abstract

High-elevation spruce-fir forests in the Appalachian Mountains of the eastern United States possess ecological, economic, and recreational value. However, red spruce (*Picea rubens* Sarg.) trees in these forests have been subject to a variety of natural and human-caused disturbances that have altered the way they grow and consequently how they respond to climate factors such as temperature and precipitation. Studies on the impacts of disturbance on the health and climate response in red spruce trees have become more important because of inconsistencies in expected climate-growth responses due to warming temperatures and other factors associated with climate change. For this study, we tested red spruce trees located near a debris slide on Mt. Le Conte, Great Smoky Mountains National Park, Tennessee, for climate-growth relationships using DendroClim2002 software to determine if climate signals prevailed in a naturally disturbed setting. Despite known periods of disturbance, red spruce on LC01 showed multiple significant climate-growth relationships with monthly mean temperature, total monthly precipitation, and monthly PDSI variables. Some were stable over the tested period 1896–2013. The strongest relationships were with previous August precipitation ($r = 0.31$, $p \leq 0.05$), current year July temperatures ($r = 0.24$, $p \leq 0.05$), and previous August PDSI ($r = 0.26$, $p \leq 0.05$). The most temporally stable relationships were a negative correlation between growth and current year April precipitation and a positive correlation with current year July

temperature. Some changes in climate-growth relationships and the emergence of new relationships occurred in the mid-20th century, and some relationship changes corresponded with disturbance event dates. However, determination of any relationship between disturbance and changing climate response in LC01 red spruce will require further study.

4.2 Introduction

The high elevation spruce-fir forests of the Appalachian Mountains are a unique and important part of mountaintop ecosystems in the eastern United States. The red spruce (*Picea rubens* Sarg.) forests are not only valued for economic and ecological reasons, but also provide opportunities to study and enjoy a forest type more common in the boreal forest zones at high latitudes. Unfortunately, this important species has come under threat due to the anthropogenic impacts of air pollution and climate change (Soulé 2011; White *et al.* 2013). Dramatic declines in growth and increased mortality of red spruce between the 1960s and 1980s have been well documented for the northern, central, and southern Appalachians, and climate change and air pollution have been listed as possible causes (McLaughlin *et al*. 1987).

Red spruce forests grow at the highest elevations in the eastern U.S. and are therefore more sensitive than lower elevation trees to changes in temperature and precipitation (White *et al.* 2013). Tree growth at both high latitudes and high altitudes is largely determined by summer temperatures (Kauppi and Posch 1985; Larsen 1989; D'Arrigo *et al*. 2013), and some of the greatest temperature increases are predicted to occur at these most sensitive locations (Hansen *et al*. 1988). Rings from trees sensitive to temperature and moisture can be used to reconstruct changes in climate over time, but inconsistencies in how trees have responded to warming temperatures in the 20th and 21st centuries have made it more important to study any changes in the relationship between trees and temperatures in recent decades. While some trees have shown increased growth and expansion of habitat because of climate warming (Innes 1991; Soulé 2011), a divergence between tree growth and temperature since the mid-20th century in some areas has contradicted expected growth responses (Briffa *et al*. 1998; D'Arrigo *et al*. 2008).

"Divergence" in tree rings describes the situation in which tree growth has diverged from temperature trends after 1950 or 1960 (Jacoby and D'Arrigo 1995; Briffa *et al*. 1998, 2000; D'Arrigo *et al*. 2004, 2008). While temperature has increased since then, tree growth rates have decreased. This response is opposite of that expected based on relationships determined in past conditions. Possible causes include increased CO_2, increased pollutants such as nitrates and phosphates, changes in soil chemistry, global "dimming," and increased UV-B radiation (D'Arrigo *et al*. 2008). However, the divergence problem has not been noted in all high latitude/altitude chronologies and cannot be termed ubiquitous (Anchukaitis *et al*. 2013). Chronologies that show divergence are problematic because they could potentially underestimate temperatures during warm periods (Anchukaitis *et al*. 2013). If trees are not responding as expected to temperature change because of anthropogenic influences, the application of uniformitarianism to tree-ring studies has to be questioned. To account for the possibility of divergence, a chronology must first be tested for temporal stability in climate-growth relationships over time before it can be used for climate reconstruction (Briffa *et al*. 1998; D'Arrigo *et al*. 2008). This is especially true in disturbed areas, where natural or anthropogenic influences on tree growth might overshadow tree responses to climate and alter climate-growth relationships over time.

For this study, we tested red spruce known to be in a naturally disturbed environment (Mt. Le Conte, Great Smoky Mountains National Park) for climate-growth relationships to determine whether climate signals had been overshadowed by disturbance signals or had persisted and maintained temporal stability despite the environment. The following research questions guided the study:

- Do significant climate-growth relationships exist between red spruce and monthly climate variables despite the location of the red spruce in a disturbed environment?
- Which detrending method works best for isolating the strongest climate signals in red spruce in the disturbed environment of Mt. Le Conte?
- If significant climate-growth relationships exist, are these relationships temporally stable over time or do major shifts dominate the signal?

4.3 Literature Review

Divergence and a history of forest decline (Siccama *et al*. 1982; McLaughlin *et al*. 1987; Johnson *et al*. 1988; LeBlanc *et al*. 1992; Busing and Pauley 1994) have made red spruce an important part of the study of changing climate-growth relationships at high latitudes/altitudes. Soulé (2011) studied changing relationships between red spruce growth, climate, CO_2, and acidic deposition on Grandfather Mountain (GFM), North Carolina. He used correlation and regression techniques to predict the effects of changing climate trends on radial growth in 47 red spruce trees. He examined red spruce growth relationships with seven climate variables:

minimum temperature, maximum temperature, mean temperature, heating-degree days, precipitation, days with precipitation greater than 0.254 cm, and total snowfall. Climate variables that showed significant influence on radial growth were included in multivariate regression models, along with CO_2 and emissions of nitrogen oxides (NO_x) and sulfur dioxides (SO_2) that could lead to acid deposition at high elevations. Red spruce on the mountain responded positively to warm temperatures, and a warming trend at GFM corresponded with increases in radial growth. Another positive relationship was found between growth and increased CO_2. Conversely, increased heating degree days, days with precipitation, and acid emissions led to decreased growth. Overall, the red spruce on GFM experienced a dramatic increase in growth, considered by Soulé (2011) to be attributed to warming temperatures, increased CO_2, and decreased acid emissions since the Clean Air Act of 1970. The red spruce trees on GFM displayed temporally stable climate signals over the time period 1956–2007.

White (2010) and White *et al*. (2012, 2013) studied changes in red spruce growth patterns in response to human disturbance and climate change on Roan Mountain, Tennessee and North Carolina. The main disturbances that affected red spruce were logging in the 1930s and infestation by the balsam woolly adelgid (*Adelges piceae* Ratzeburg). White *et al*. (2012) found that logging in the 1930s drastically impacted the composition and structure of the spruce-fir forest on Roan Mountain. Large, canopy-dominant red spruce were harvested during the logging period, which allowed Fraser fir to dominate in the current era. White *et al*. (2013) then analyzed the impacts of disturbance on the ability of red spruce to record climate signals in a highly disturbed environment. In light of the emerging "divergence problem" and the highly disturbed landscape found on Roan Mountain, they tested the temporal stability of regional climate signal in a chronology from 1874–2009. The chronology was separated into pre-logging and post-logging eras to see if this disturbance altered climate sensitivity or the strength of climate signal.

The strongest relationship found was a negative correlation between tree growth and previous July and September temperature. Relationships with precipitation and drought indices were less influential on tree growth, but a significant ($p \leq 0.05$) negative relationship was found between red spruce growth and current year May precipitation. Above-average rainfall in the spring led to decreased growth in red spruce. White (2010) found a shift in temperature sensitivity in red spruce around 1950. Following this shift, red spruce showed a strong and consistent inverse relationship with previous summer temperatures, but relationships pre-1950s had been positive and less consistent. A shifting climate response in red spruce in the mid-20th century was also noted by Cook *et al*. (1987), Johnson *et al*. (1988), and Cook and Johnson (1989), with proposed links to climate change. The changing climate-growth relationships over time found by White *et al*. (2013) were likely related to disturbances, such as the balsam woolly adelgid infestations or acid deposition, and such instabilities called into question the overall temporal stability of high-elevation red spruce at the Roan Mountain site. Overall, climate sensitivity in red spruce was unstable over time, leading White (2010) to conclude that stand dynamics, including disturbance regimes, may play a larger role than climate in determining the forest composition and succession on Roan Mountain.

The discovered temporally unstable climate-tree growth relationships found in red spruce on Roan Mountain highlighted the importance of testing temporal stability before performing climate reconstructions. Unstable climate-growth relationships are not ideal for climate reconstruction. Frequently disturbed forests may be limited more by the frequency of disturbance than by climate factors such as temperature and precipitation (White 2010). White *et al.* (2013) could not attribute red spruce decline on Roan Mountain solely to the logging disturbance, but they suggested that it was due to a likely combination of changing disturbance regimes, acid deposition, insect outbreaks, and climate change. Disturbances, including climate change, led to reduced temporal stability in the studied forest (White *et al*. 2013).

Biermann (2009) also noted a mid-20th century shift in climate response during her study of changing climate-growth relationships in shortleaf (*Pinus echinata* Mill.) and pitch (*Pinus rigida* Mill.) pines of the Great Smoky Mountains. Using correlation, response function, and moving interval analysis in DendroClim2002 (Biondi and Waikul 2004), Biermann found associations between growth in yellow pine and winter mean minimum temperatures, spring precipitation, and growing season precipitation at five sites in GSMNP. Positive relationships with positive phases of Atlantic sea surface temperature (SST) anomalies and the North Atlantic Oscillation (NAO) were also noted. However, these relationships were not temporally stable. A mid-20th century weakening of the relationship with growing season moisture, and a shift to winter and fall temperature relationships, showed an inconsistent trend in climate-growth relationships, making the yellow pine chronologies developed by Biermann unsuitable for climate reconstruction.

Li (2011) also discovered temporally unstable climate-growth relationships and a mid-20th century shift during study of climate signals in pine species at three sites along a coast-to-inland transect in the southeastern United States. Correlation, response function, and moving interval analysis in DendroClim2002 (Biondi and Waikul 2004) were used to test for temporal stability in longleaf pine (*Pinus palustris* Mill.) sampled from preserved wood in the Hope Mills crib dam and living nearby trees, North Carolina; in Table Mountain Pine (*Pinus pungens* Lamb.) collected from Linville Mountain, Pigsah National Forest, North Carolina; and in shortleaf and pitch pine from the Gold Mine Trail of western GSMNP. At the Gold Mine Trail site, the strongest relationship was with winter temperature, but relationships with precipitation were strongest at the other two sites. A shift in climate response occurred in the 1950s at the Linville Mountain and Gold Mine Trail sites. After the 1960s, relationships with growing season precipitation weakened and relationships with wintertime temperature signals appeared, similar to results found by Biermann (2009). It will be important to note if the mid-20th century shift seen by both Biermann (2009) and Li (2011) also occurred in GSMNP red spruce.

4.4 Study Site

Debris slides are a common natural disturbance on Mt. Le Conte, GSMNP, where thin soil layers underlain by tilted Anakeesta Formation layers are prone to sliding after heavy rainfall (Hadley and Goldsmith 1963; Moore 1988; Henderson 1997). We chose the study site, Le Conte 01 (LC01), because of its proximity to an area of frequent debris slide disturbance. We sampled trees on or near (within five meters) the boundaries of a debris slide complex that consists of three slide areas joined at the base and bisecting the Alum Cave Bluffs Trail in GSMNP at N 35.65100 W 83.44100 (approximately 1800 m elevation) about 6.5 km from the trailhead at Hwy 441. LC01 lies on the rust-stained Anakeesta Formation, which includes metasiltstone, phyllite, slate, metasandstone, schist, and dolomite (Hadley and Goldsmith 1963).

The climate at LC01 is cool and moist because of high elevations, high winds, winter snow, clouds, and heavy rains. In GSMNP, the high elevations of mountain peaks (the elevation of Mt. Le Conte is 2010 m) can experience daily temperatures 9–12 °C cooler than at the base, and annual precipitation values over 2000 mm are common (Shanks 1954). As elevation increases and temperature decreases up the mountain, forest type transitions from hardwood to spruce-fir, with red spruce beginning around 1370 m, spruce and fir at 1670 m, and Fraser fir (*Abies fraseri* (Pursh.) Poir) above 1900 m (Whittaker 1956). The LC01 site contains a mixture of tall red spruce trees and smaller Fraser firs. Because the balsam wooly adelgid greatly affected Fraser fir in the southeastern Appalachians (Busing and Pauley 1994), the National Park Service forbids the coring of Fraser fir. This regulation restricted sampling to red spruce.

Understory species at LC01 consist primarily of Catawba rhododendron (*Rhododendron catawbiense* Michx.), spinulose shield fern (*Dryopteris austriaca* var. spinulose (Muell.) Fiori), smooth blackberry (*Rubus canadensis* L.), hobblebush (*Viburnum alnifolium* Marshall), Blueridge blueberry (*Vaccinium pallidum* Aiton), southern mountain cranberry (*Vaccinium erythrocarpum* Michx.), and mountain oxalis (*Oxalis montana* Raf.) (Braun 1950). The main slide area of LC01 is covered by a thick layer of Sphagnum moss and grasses, including Cain's reedgrass (*Calamagrostis cainii* Hitchc.) and wretched sedge (*Carex misera* Buckley) (Feldkamp 1984). The purple-flowered narrowleaf gentian (*Gentiana linearis* Froel.) covers the grassy portion of the slide during the warm months (Feldkamp 1984). Other plants seen at LC01 include Michaux's saxifrage (*Spatularia michauxii* Britton), skunk goldenrod (*Solidago glomerata* Michx.), and Rugel's ragwort (*Rugelia nudicaulis* Shuttlew. ex Chapm.) (Wise and Petersen 1998). Trees on the perimeter of the slide are rooted in very thin soil and surrounded by woody debris. Most trees have exposed roots with cavities underneath that reveal bedrock on the steep slopes, suggesting that perimeter trees might have survived exposure of their roots by the debris slide. Such exposure might also be caused by the limited amount of soil on the steep slopes of the Anakeesta formation at high elevations.

4.5 Methods

We chose LC01 from a list of debris slide scars based on efficient access and safety, as well as the identification of red spruce accessible near slide scar boundaries. To identify a disturbance signal, we chose to sample red spruce trees based on proximity to the main slide area. We selected trees within five meters of slide boundaries because these trees would be most likely to have experienced growth release because of the removal of competition, growth suppression following scarring or removal/exposure of roots or injury to treetops by debris, or both (Shroder 1980; Stoffel and Bollschweiller 2008 and 2009; Clague 2010). Trees chosen for sampling could not be cut down to obtain cross sections, so sampling was limited to increment cores. We collected at least two cores per tree from 30 trees using a Haglof 3-thread increment borer to obtain the history of disturbance for the area and the data needed to analyze climate-growth relationships in disturbed red spruce.

We sanded all core samples with a belt sander using progressively finer sandpaper, beginning with ANSI 80-grit (177–210 μm) and finishing with ANSI 400-grit (20.6–23.6 μm) to increase visibility and accuracy when measuring ring widths (Orvis and Grissino-Mayer 2002). Once sanded, we marked tree rings using the standard decadal dot notation, starting at the outermost complete ring and counting towards pith (Stokes and Smiley 1996; Speer 2010). All samples were taken from living trees, so the date of the outermost ring was known. Counting inward from bark, we dated all rings, and the year of the innermost complete ring was noted for measuring. We measured total ring widths to 0.001 mm accuracy, starting with the innermost complete ring, using a Velmex measuring system and MEASURE J2X software.

We internally crossdated all measured series using COFECHA (Holmes 1983; Grissino-Mayer 2001) to properly place each series in the correct temporal alignment with the other series. A correlation threshold of 0.40 is used in the Southeastern U.S. (International Tree-Ring Data Bank (ITDRB) 2013) to ensure correct crossdating. Segments analyzed were 40 years in length lagged by 20 years, and the critical correlation for segments was 0.37 (Grissino-Mayer 2001). Internal crossdating is necessary to determine the date of the final ring and to identify missing rings. We used the presence of latewood-earlywood to determine the last possible complete ring because trees were sampled during and after the 2013 growing season. We developed the final raw chronology for the LC01 site using the program ARSTAN (Cook 1985).

We removed age-related growth trends and disturbance signals using detrending techniques in the program ARSTAN (Cook 1985). The detrending process fits a line or curve to raw ring-width data, then generates an index based on predicted versus actual growth. The index allows all trees to contribute equally to the final chronology. Detrending also removes noise to isolate the desired signal. Aggregate tree growth is a function of age-related growth trends, climate, internal and external disturbances, and error. For this study of temporal stability, we considered age-related trends and disturbance to be noise that needed to be removed to isolate the climate signal. To determine the best detrending curve fit needed to isolate climate, we used instrumental climate data to perform tests for appropriate flexibility of the spline curve to remove disturbance but retain climate.

To identify the appropriate spline curve for maintaining the strongest climate signal, we tested five detrending methods: four using splines with lengths of 15, 20, 25, and 32 years, and one using linear and exponential trend lines, using DendroClim2002 (Biondi and Waikul 2004). We obtained instrumental climate data for monthly average temperature (MNTM), total monthly precipitation (TPCP), and monthly Palmer Drought Severity Index (PDSI) from the National Climatic Data Center (NCDC) divisional data for Eastern Tennessee (NCDC 2014). We detrended the LC01 chronology with each of the lines and splines individually to create five separate standard chronologies. We then individually entered each of these into DendroClim2002 and tested, using correlation analysis, for relationships with MNTM, TPCP, and PDSI variables from the Eastern Tennessee climate divisional data. To determine which detrending method provided a higher number of stronger relationships, we compared results from each method (Fig. 4.1, Table 4.1).

We continued climate response analysis using DendroClim2002 (Biondi and Waikul 2004). We used bootstrapped correlation analysis to test for relationships between individual climate variables and standardized tree-ring indices in a chronology, and we used forward evolutionary analysis to detect changes in climate-growth relationships or in the strength of relationships over time (White *et al*. 2013). Consistent relationships over time indicate temporal stability, but frequently changing or reversing relationships over time indicate temporal instability. We tested the climate variables MNTM, TPCP, and PDSI for the period extending from previous April to current October to include the lagged effect of influences from previous years on current year growth. Forward evolutionary analysis tested the common period 1896–2013 and used a baselength interval of 38 years, twice the number of months represented by the climate variables (19 months each for MNTM, TPCP, and PDSI), as suggested by Biondi and Waikul (2004). In forward evolutionary analysis, the start year of the interval remains fixed and, for each test, the end year is increased by one. Intervals then move forward in time through the tested period, adding one year at a time while the first year remains fixed. Results from forward evolutionary analysis covered the period 1933–2013. In addition to individual monthly climate variables, we also tested seasonal combinations of variables were also tested based on patterns seen in the detrending method tests. Seasonal variables tested were summer temperature (June-August), winter temperature (January-March), spring precipitation (April and May), summer precipitation (July and August), and fall PDSI values (August-November).

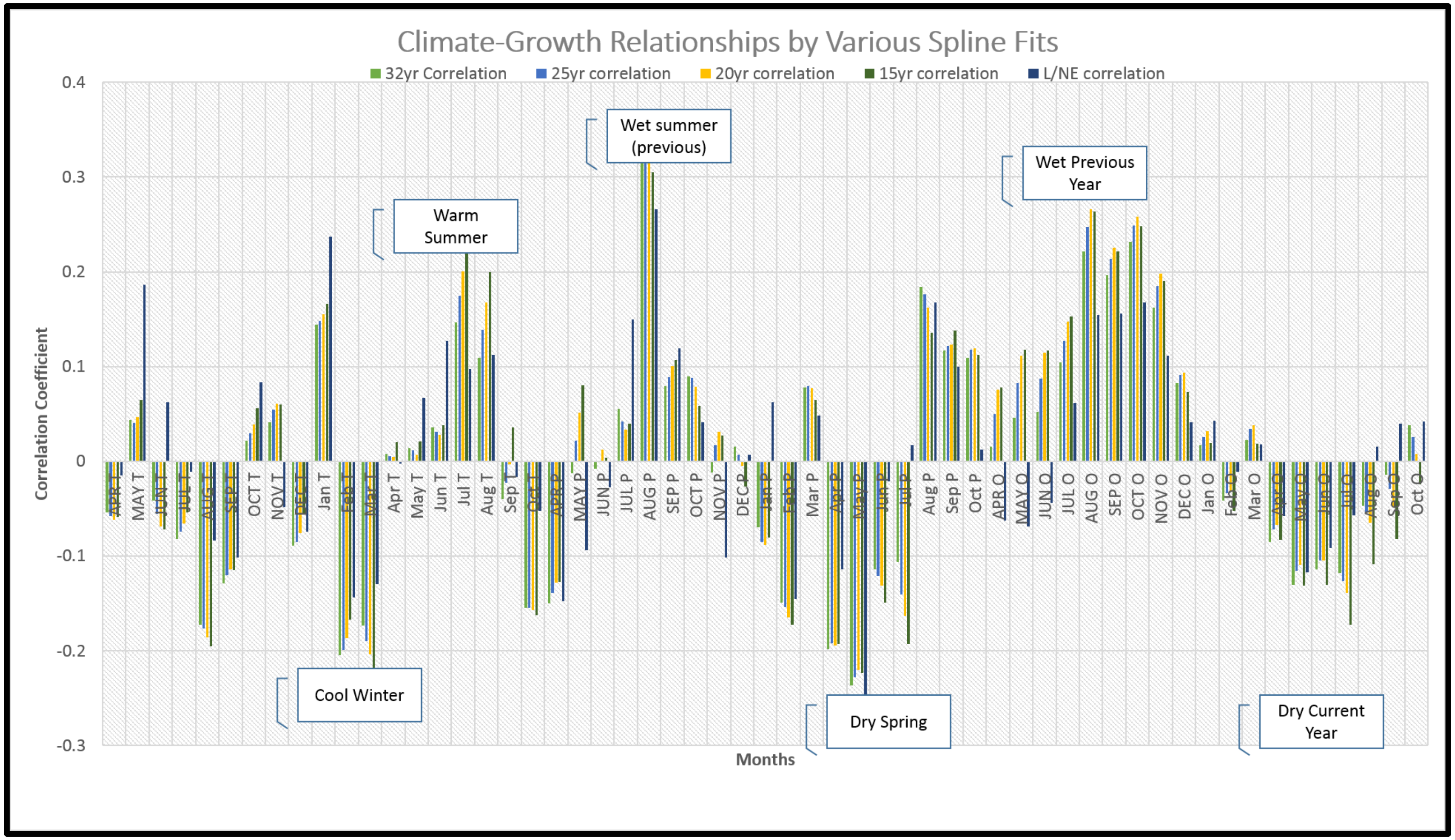


Figure 4.1: Correlations between climate and growth resulting from detrending tests using 32, 25, 20, and 15 year splines, as well as linear/negative exponential line fits. Months listed in all capital letters represent previous year, and lower case letters are current year. The climate variables are mean monthly temperature (T), total monthly precipitation (P) and monthly PDSI (O). This graph was used to identify which method produced the strongest relationships but also overall patterns in favorable growth conditions for red spruce at LC01.

Table 4.1: Table of significant (p ≤ 0.05) correlations found in the detrending tests. Months listed in all capital letters represent previous year, and lower case letters are current year. Climate variable are monthly mean temperature (T), total monthly precipitation (P), and monthly PDSI (O). Highlighted cells indicate the highest correlation per monthly variable ≥ 0.20 or ≤ –0.20. The 15-year spline was chosen based on the number of significant relationships and the higher correlations.

Results from Standardization Tests					
Climate Variable	**Linear/Neg. Exp.**	**32 Year**	**25 Year**	**20 Year**	**15 Year**
AUG T	–	–	–	–	-0.20
Jan T	0.24	–	–	0.16	0.17
Feb T	–	-0.20	-0.20	-0.19	-0.17
March T	–	-0.17	-0.19	-0.20	-0.22
July T	–	–	–	0.20	0.24
Aug T	–	–	–	0.17	0.20
AUG P	0.27	0.33	0.34	0.33	0.31
Feb P	–	–	–	-0.16	-0.17
April P	–	-0.20	–	–	–
May P	-0.25	-0.24	-0.23	-0.22	-0.22
July P	–	–	–	–	-0.19
Aug P	0.17	0.18	0.18	0.16	–
AUG O	0.15	0.22	0.25	0.27	0.26
SEP O	–	0.20	0.21	0.23	0.22
OCT O	0.17	0.23	0.25	0.26	0.25
NOV O	–	–	0.18	0.20	0.19
July O	–	–	–	–	-0.17

4.6 Results

The final raw and standard LC01 chronologies (Fig. 4.2) covered the period 1792–2013 and consisted of 48 dated tree-ring series from 30 individual red spruce trees. The mean segment length was 148.8 years. The interseries correlation was 0.53 ($p \leq 0.0001$), which is exceptionally high for southeastern trees. The interseries correlation was above the critical threshold of 0.40 for southeastern trees (ITRDB 2014a) and slightly below the average (0.56) for red spruce (ITRDB 2014b). The mean sensitivity was 0.20, slightly below the average (0.22) for red spruce (ITRDB 2014b). Mean sensitivity measures changes in year-to-year ring width, with high values indicating higher sensitivity to climate variables. Values vary from high for drought-sensitive conifers (0.65) to low for complacent trees (0.15) that experience few limiting factors in favorable environments (ITRDB 2014b). In the southeastern U.S., a minimum mean sensitivity of 0.20 is typically required to indicate the climate sensitivity needed for crossdating.

Following tests of the six detrending methods, we evaluated the results based on which detrending method revealed the most relationships between climate and growth and which consistently showed higher correlations with climate variables. The 15-year spline resulted in a standard chronology that had the strongest climate signal (Table 4.1). We chose the 15-year spline curve to develop the final standard chronology. The detrending tests using all methods revealed some patterns in conditions favorable to positive growth in red spruce: a cool winter, a dry spring, a warm summer, a wet previous year, and a drier current year (Fig. 4.1). The strongest relationship for both temperature and precipitation found using the 15-year spline detrended chronology was with previous August precipitation ($r = 0.31$, $p \leq 0.05$) (Fig. 4.4). Other strong relationships included current March temperature (–0.22, $p \leq 0.05$), current

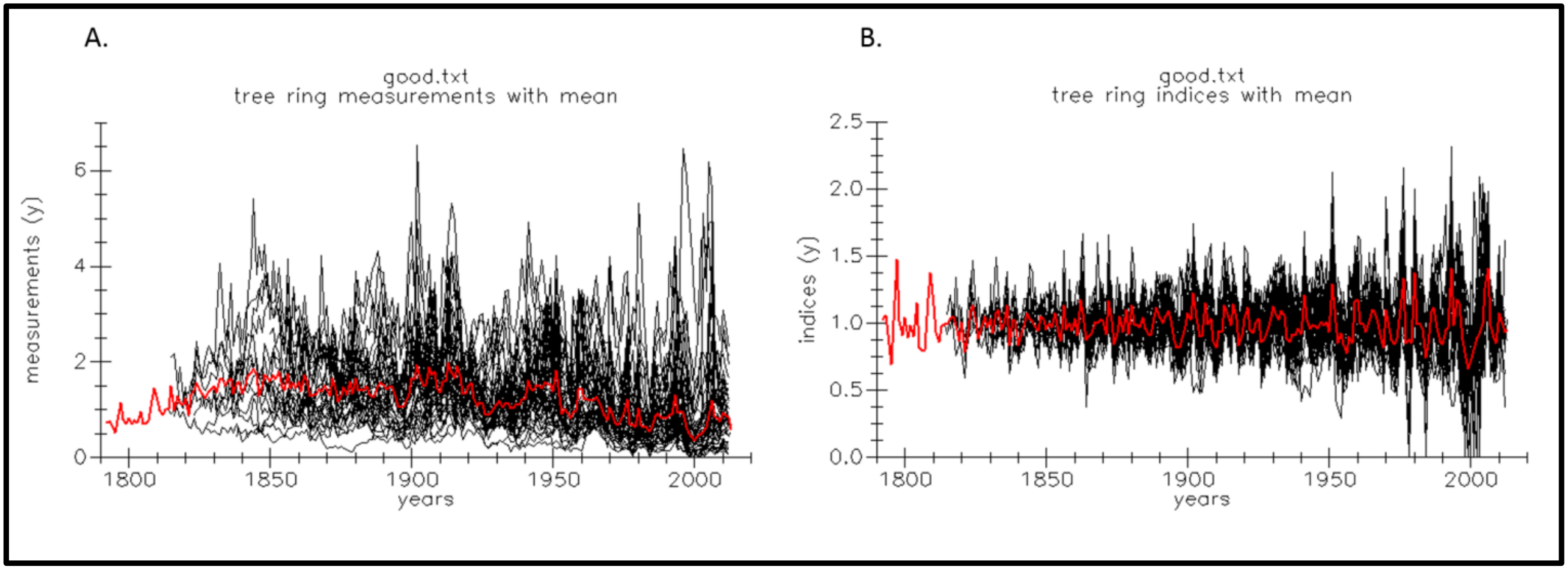


Figure 4.2: A. Le Conte tree ring series of raw ring widths and the average (red) chronology developed with ARSTAN. **B.** LC01 final chronology (red) standardized using 15-year spline in ARSTAN.

May precipitation (–0.22, $p \leq 0.05$), current July temperatures (0.24, $p \leq 0.05$), and previous August, September, and October PDSI (0.26, 0.22, 0.25, $p \leq 0.05$, respectively). Four of the five tested seasonal variables had significant ($p \leq 0.05$) relationships with growth in red spruce: previous summer precipitation (0.21), previous fall PDSI (0.25), current summer temperatures (0.21), and current spring precipitation (–0.30) (Fig. 4.3).

Forward evolutionary analysis revealed temporally stable relationships between red spruce growth and both temperature and precipitation variables (Fig. 4.4). The red spruce growth relationship with current July temperatures was temporally stable through all of the 117-year period except when the years 1976–1983 were added, which resulted in correlations below 0.20. A relationship with current January temperature remained stable up to the 1970s, and a weaker relationship with current March temperatures emerged after the 1960s. Relationships with precipitation revealed a higher level of temporal stability, especially with current April precipitation, which remained strong and stable until near the end of the tested period or until the late 2000s. A relationship with current May precipitation was stable but weaker beginning around 1950. The strongest climate variable relationship revealed through correlation analysis, previous August precipitation, was stable after 1950, with pockets of strong correlation periods in earlier years. A positive relationship with previous May precipitation weakened in the 1970s. No PDSI relationship was found to be temporally stable. A weaker but stable relationship with previous October PDSI emerged in the 1950s. However, PDSI variables showed major shifts in overall correlation values through time, indicating that some events caused major shifts in red spruce growth relationships with monthly PDSI in the 1940s, 1950s, and 1974 (Fig. 4.5).

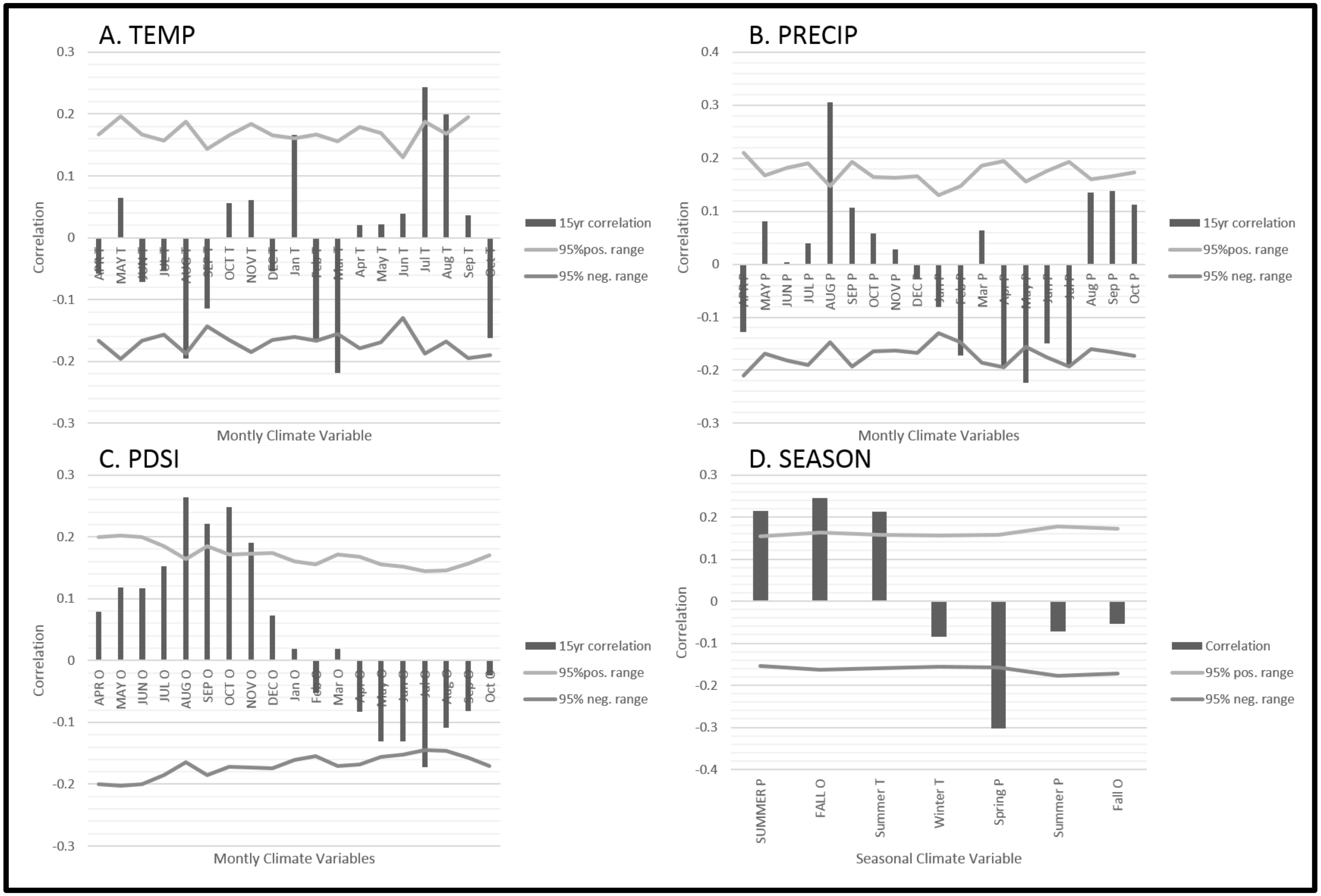


Figure 4.3: Graphs of climate-growth relationships (correlations) with MNTM, TPCP, PDSI and seasonal climate variables. Lines represent 95% significance intervals calculated in DendroClim2002 (Biondi and Waikul 2004).

4.7 Discussion and Conclusion

Despite living in a known area of disturbance, red spruce at LC01 showed multiple significant ($p \leq 0.05$) growth relationships with climate variables over the period 1896–2013. A few of these relationships were also temporally stable. The strongest relationship was with previous August precipitation ($r = 0.31$), but the strongest seasonal relationship was with current spring precipitation ($r = –0.30$). A negative relationship with current April precipitation was temporally stable over the longest period with only one weakened period in the late 2000s. The general pattern favorable to red spruce growth, revealed in climate-growth relationships of the final 15-year detrended chronology, was a dry and cool current spring followed by a warm and dry current summer. However, red spruce also favored a wet previous summer, according to both the strong positive previous August relationship and the relationships with fall and summer previous year PDSI values.

In contrast to the findings in previous studies (Biermann 2009; White 2010; Li 2011), we did not discover any major shifts from one climate-growth relationship to another (temperature to precipitation or vice versa) during the mid-20th century. However, a few notable changes in climate-growth relationships occurred around this time. The relationship with current January temperature weakened and was no longer stable after the 1960s, and a weak relationship with current March temperature emerged after the 1960s. The relationship with previous August precipitation became more dominant after the 1950s, but the relationship with previous May precipitation became less pronounced after the 1960s. A weak relationship with current May precipitation also emerged after the 1950s. For PDSI, the weak and less stable previous October PDSI relationship emerged and seemed to strengthen slightly after the 1950s. No shifts

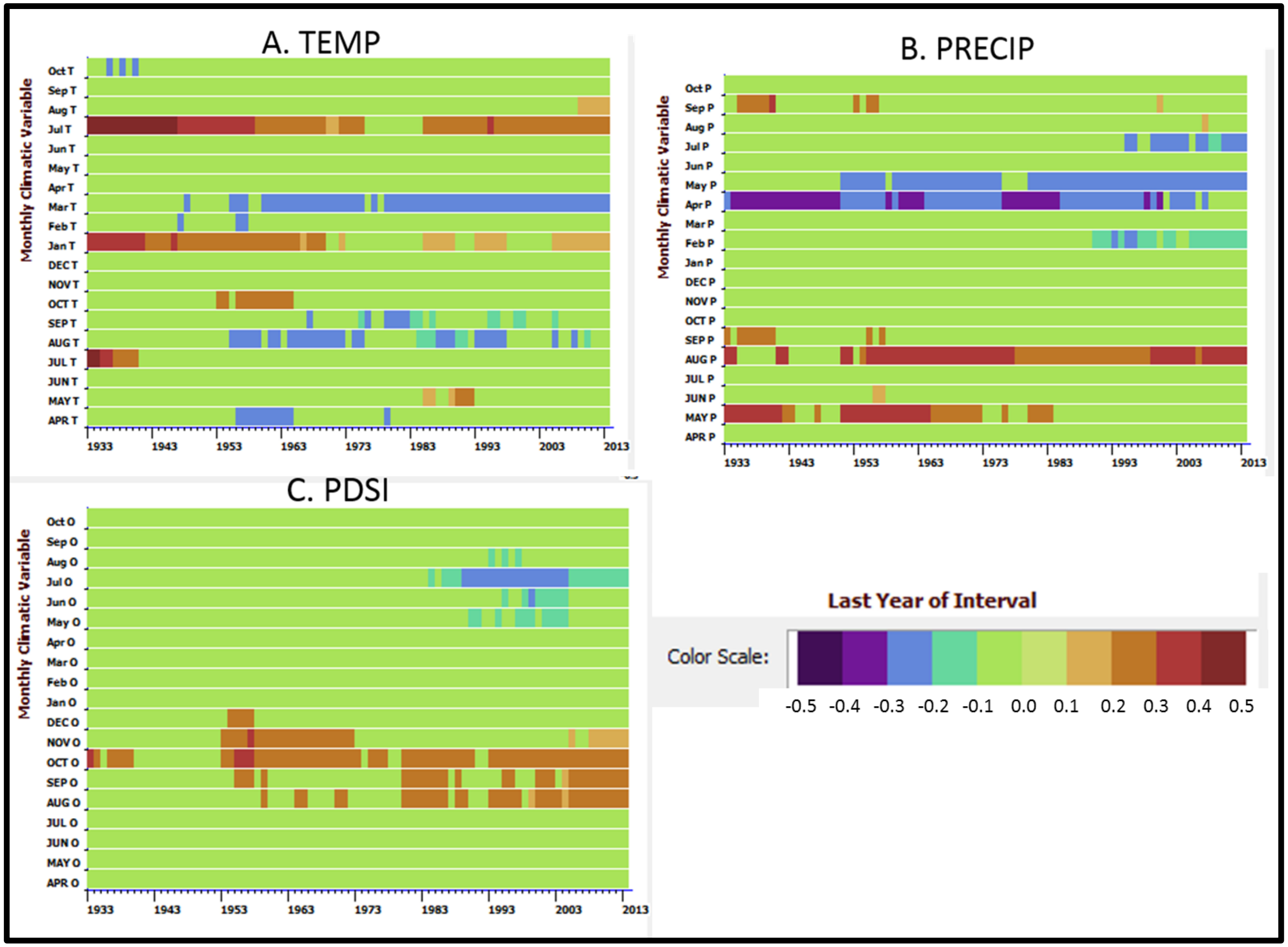


Figure 4.4: Results from DendroClim2002 forward evolutionary analysis for growth relationships with **A.** Temperature **B.** Precipitation and **C.** PDSI. Red and orange colors indicate positive climate-growth relationships, and blue and purple bars indicate negative climate-growth relationships. Dark red and purple indicate the strongest relationships. Solid or near solid bars across the large portions of the studied period indicate temporal stability. The most temporally stable relationships throughout were negative with current April precipitation and positive with current July temperature.

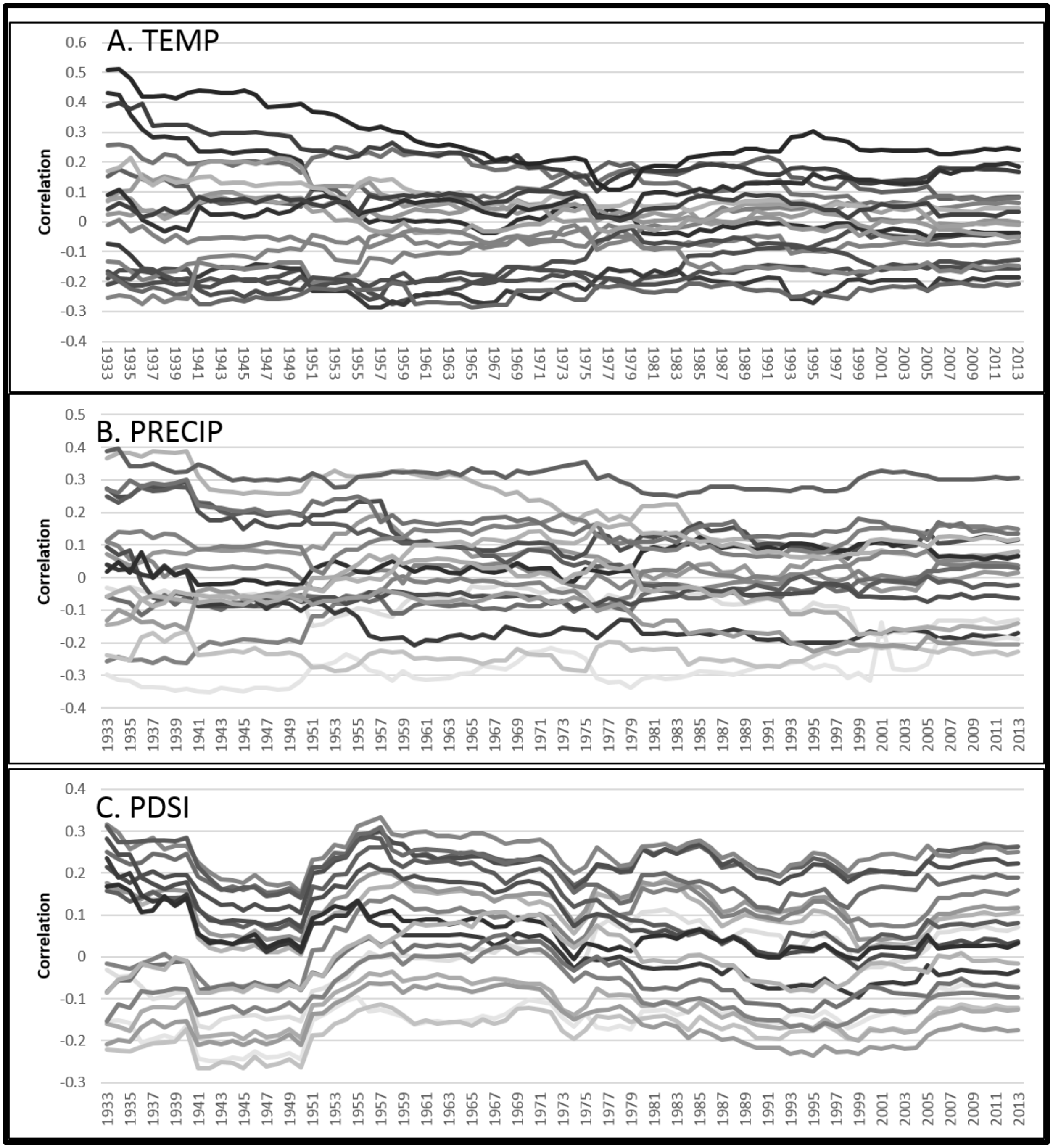


Figure 4.5: Correlation evolution graphs of results from forward evolutionary analysis in DendroClim2002 showing shifts in 19 climate variables (previous April to current year October temperature, precipitation, and PDSI) and their correlations with tree growth over time and spanning the period 1933–2013. **A.** Monthly mean temperature. **B.** Total monthly precipitation. **C**. PDSI. Note the major shifts in correlations with PDSI in the 1940s followed by a shift in the 1950s, as well as the notable dip around 1974.

from precipitation to temperature relationships, as seen in the reviewed literature, were noted. The strongest and most temporally stable relationships, according to forward evolutionary analysis, were negative with current April precipitation and positive with current July temperature, and these relationships remained the most constant and temporally stable through the studied period. No changes in the presence or strength of growth relationships with these variables were experienced during the mid-20th century. Warm temperatures were favorable, and red spruce growth did not diverge from summer temperatures after the mid-20th century.

Changes in climate relationships, especially the emergence of new relationships near the mid-20th century, are notable in this study because a known debris slide event occurred during this time. Correspondence may be coincidence but is worth noting. On September 1, 1951, a cloudburst on Mt. Le Conte led to multiple debris slides, including the one studied at LC01 (Bogucki 1970). Perhaps because of disturbance, climate-growth relationships emerged that had not previously existed (at least in the studied common period). In addition, the correlation evolution graphs revealed shifts in overall correlations during the mid-20th century, especially for PDSI. A shift in correlations with monthly PDSI occurred in the 1940s, followed by a shift in correlations in the 1950s, and a notable dip occurred around 1974 (Fig. 4.5). If these shifts are found to correspond with debris slide events, the argument that disturbance can alter climate signal may be further supported. The disturbance signal could possibly overwhelm the climate response. Trees that experience reduced competition and growth release should be less apt to record a drought signal. However, correspondence between disturbance dates and changes in climate response may be coincidence only and merits further investigation. The possible role of disturbance in initiating, changing, or eliminating climate relationships is worth future study.

Still, it is interesting to note that climate-growth relationships were able to persist despite frequent disturbance at LC01. The existence of a significant climate signal means that isolating geomorphic disturbances from those caused by climate will be more difficult at the site.

CHAPTER FIVE

Dendrogeomorphic Analysis of Debris Slides on Mount Le Conte, Great Smoky Mountains National Park, Tennessee, U.S.A.

This chapter is intended for publication in the journal *Geomorphology*. I developed the research topic with my advisor and second author, Dr. Henri Grissino-Mayer. The use of "we" throughout the text refers to me and Dr. Grissino-Mayer, who assisted with project development, site selection, field collection, and text editing. My contributions to this chapter include field collection, processing and dating of samples, data analysis, interpretation and graphic displays of results, and writing the manuscript.

5.1 Abstract

Research conducted during the past 30 years tested the use of tree rings to date mass movement events in the mountain areas of Europe and the western United States. However, few studies have been performed in the eastern U.S., where debris flows, landslides, and rock falls in the Appalachian Mountains pose a common threat to human life and property. One area of particular interest is Great Smoky Mountains National Park (GSMNP). For this study, we tested mature red spruce (*Picea rubens* Sarg.) trees located on or near a debris slide boundary on Mt. Le Conte (LC01) in GSMNP, Tennessee, for a disturbance signal that indicates debris slide activations or reactivations at the site. To first determine if climate influences prevailed at the site and might contribute to abnormal growth patterns, we initially tested sampled trees for climate-growth relationships using DendroClim2002 software. Red spruce on LC01 showed multiple significant climate-growth relationships with monthly and seasonal mean temperature, total precipitation, and PDSI variables. Next, we analyzed suppression and release sequences using a combination of visual and graphical inspection with JOLTS disturbance-detecting software. Visually and statistically detected onset dates identified growth disturbances, but knowledge of significant climate responses in tree growth prompted the use of an ensemble strategy to minimize the influence of climate on the disturbance signal and isolate growth responses in red spruce caused only by debris slide events at the study site.

We created a difference chronology for analysis in OUTBREAK, compared this with local reference chronologies and with local climate data, and modelled climate using regression residuals in Excel. Combined visual and statistical results provided a list of 20 possible debris slide dates but only three were further supported from results in the ensemble methods: 1909, 1951, and 1981. Results highlighted the importance of the use of an ensemble strategy to better isolate debris slide signals from abnormal growth patterns caused by climate. We found that both climate and debris slide signals were present in the tree-ring record, and disturbance detection alone was not adequate for identifying debris slide event years. Climate-growth analysis and subsequent removal of climate signals using a control chronology or other methods should always be an initial step in dendrogeomorphic studies.

5.2 Introduction

The study of mass movements has become increasingly important in areas where development pushes the limits of the natural landscape. Where towns and cities have grown next to unstable slopes, improved understanding of geomorphic processes and frequencies of hazardous events is crucial. Dendrogeomorphology has become a significant part of land-use planning in areas prone to landslides, avalanches, debris flows, mudflows, and other forms of slope failure (Butler *et al*. 1987; Clague 2010; Saez *et al*. 2012; Shroder 1980; Stoffel 2010; Stoffel and Bollschweiler 2008, 2009). By determining frequencies of mass movement events for mountain areas, land management personnel can better design mass movement mitigation and determine development suitability (Clague 2010; Stoffel 2010). One area that would benefit from improved methods for mass movement study is the national park system, where a better understanding of natural hazards is not only prudent for the safety of recreational visitors, but also for the sake of improved understanding of the natural landscapes within different parks. Information about landscapes and different types of mass movements, obtained through dendrogeomorphic methods, extends biophysical data further into the past where aerial photographs, field surveys, and archival records might not reach (Stoffel and Bollschweiler 2008).

Dendrogeomorphic research has provided information on historic mass movement events in the western United States and the mountain regions of Europe, and a few studies have been conducted in the more eroded and less prominent Appalachian Mountains of the eastern United States. Debris flows and landslides in this region pose a common threat and scar the faces and channels of mountains throughout the Appalachian region (Wieczorek and Morgan 2008). In Great Smoky Mountains National Park (GSMNP), landslides, debris flows, and rock falls frequently disrupt transportation routes for hikers and motorists (Henderson 1997). While these natural hazards aggravate and sometimes cause harm, they also provide a prime research opportunity for land managers and scientists who seek to understand the characteristics of local mass movements. Dendrogeomorphology can discover additional landslides and debris flows no longer visually evident or not reported in historical records and contribute to the development of historical mass movement inventories (Stoffel and Bollschweiler 2008). Debris slides are a common feature on the slopes of Mt. Le Conte, GSMNP, but information on their dates of origin and reactivation is incomplete (Henderson 1997). We undertook a dendrogeomorphological analysis of debris slides on Mt. Le Conte to provide the missing information needed to complete the record and determine debris slide frequencies.

5.3 Research Questions

For this study, we used dendrogeomorphic methods to determine the history of debris slide activations or reactivations on a debris slide scar of Mt. Le Conte in GSMNP. To first determine the influence of climate on red spruce growth and disturbance signals at the site, we tested sampled trees for climate-growth relationships. A significant climate influence at the study site prompted us to use additional methods to remove this influence and better isolate a debris slide signal. After the removal of the climate influence, disturbed growth caused by the debris slide event provided event dates and a disturbance history for the site. The following research questions guided the study:

- What are the date(s) of slide activations or reactivations at the debris slide site LC01?
- What are the possible triggers of these debris slides?
- Which forms of tree-ring evidence worked best to identify debris slide dates in GSMNP?

5.4 Study Site

The study site, Le Conte 01 (LC01), was chosen because of its proximity to an area of frequent natural disturbance. We sampled trees on or within five meters of the edge of a debris slide complex that consists of three slide areas that join at their base (Fig. 5.1) and cross the Alum Cave Bluffs Trail in GSMNP at N 35.65100 W 83.44100 (approximately 1800 m elevation) about 6.5 km from the trailhead at Hwy 441 (Fig. 5.2). The slide scar drains into the headwaters of the Trout Branch watershed. The westernmost slide section is younger than the primary slide area and is estimated to have occurred between the years of 1992 and 1998, based on historical imagery in Google Earth. In 1993, a summer storm caused debris slides and storm damage along the lower portions of the Alum Cave Bluffs Trail (Henderson 1997; Wise and Petersen 1998), and this event is the most likely trigger of the addition to LC01. The slide head/scarp of LC01 is a crescent-shaped area of exposed Anakeesta bedrock, grasses, and mosses above the Alum Cave Bluffs Trail (Fig. 5.3). Such geomorphic features are common to slide areas in the Appalachians and indicative of a "water blowout" triggered slide (Hack and Goodlett 1960). The slide scarps of water blowouts form in areas where water collects on steep slopes and causes slope failure following saturation (Bogucki 1970; Hack and Goodlett 1960). After heavy rainfall, water quickly saturates thin soils and reaches bedrock, flowing downslope underneath the soil and causing unstable soil and roots to slide along the steep tilt of the bedrock (Wise and Petersen 1998). The exposed surface is planar, following the dip of the Anakeesta formation, and is not hollowed out or dipped backwards due to rotation. The combination of the planar slide surface of the scarp and later funneling into a debris chute led to the use of the term "debris slide," a hybridization of debris flow and translational landslide (Easterbrook 1999), in this study.

We estimated the most recent debris slide event at LC01 to be 60 to 70 years old based on preliminary field estimates from growth release in tree rings, supported by Wise and Petersen (1998) who put the event at 1948. Feldkamp (1984) estimated an age of greater than 50 years for the slide during her study of debris slide revegetation. These date estimates may represent the September 1, 1951 cloudburst event studied by Bogucki (1970). He included a picture of the slide studied at LC01 in the manuscript but focused on slides that occurred in a separate drainage, the Styx Branch drainage, slightly to the east of LC01 on the other side of a ridge. Trees sampled at LC01 should mark the effects of the September 1951 cloudburst event in the

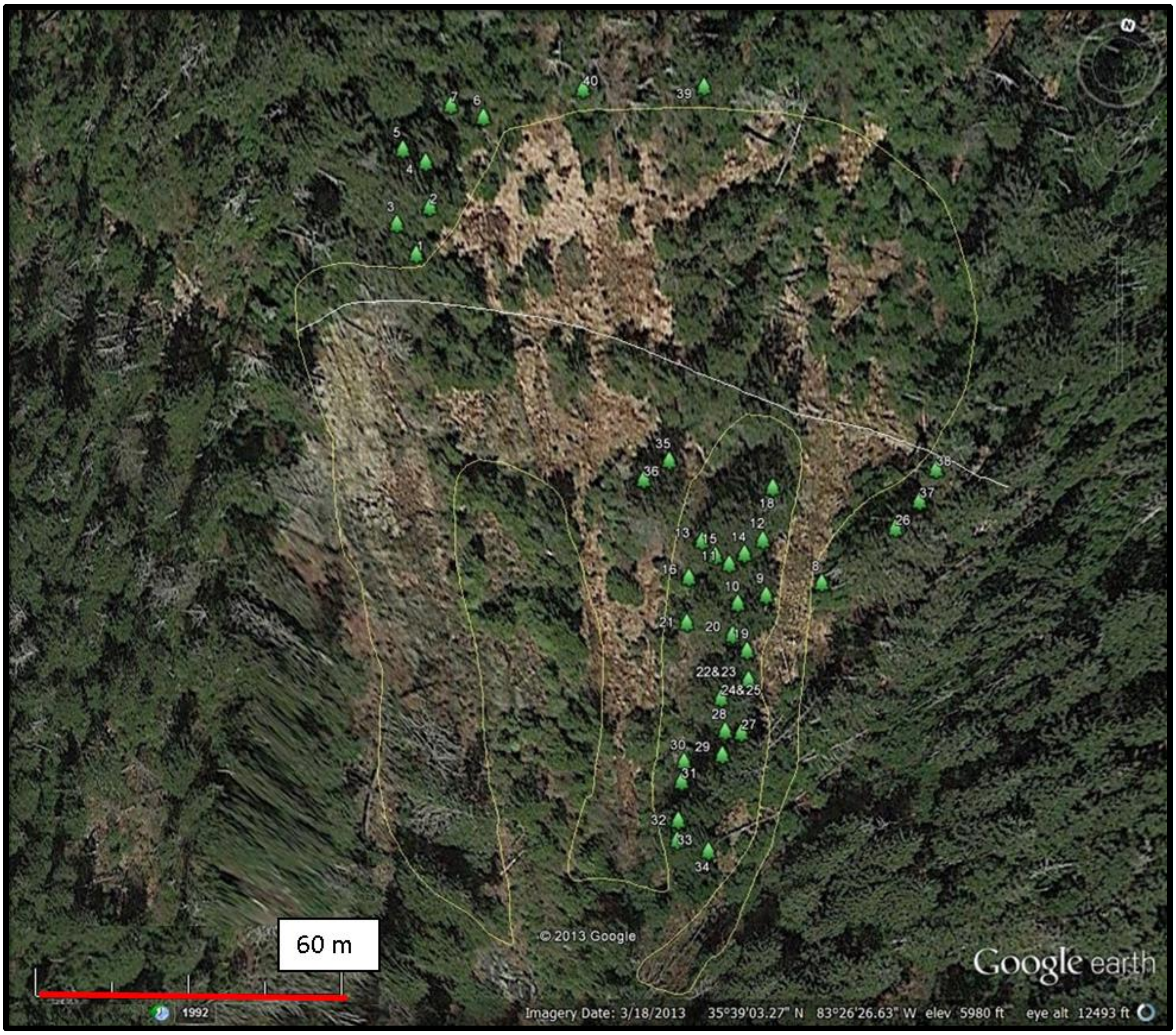


Figure 5.1: Google Earth image of LC01 debris slide and sampled trees. The white line indicates the Alum Cave Bluffs trail.

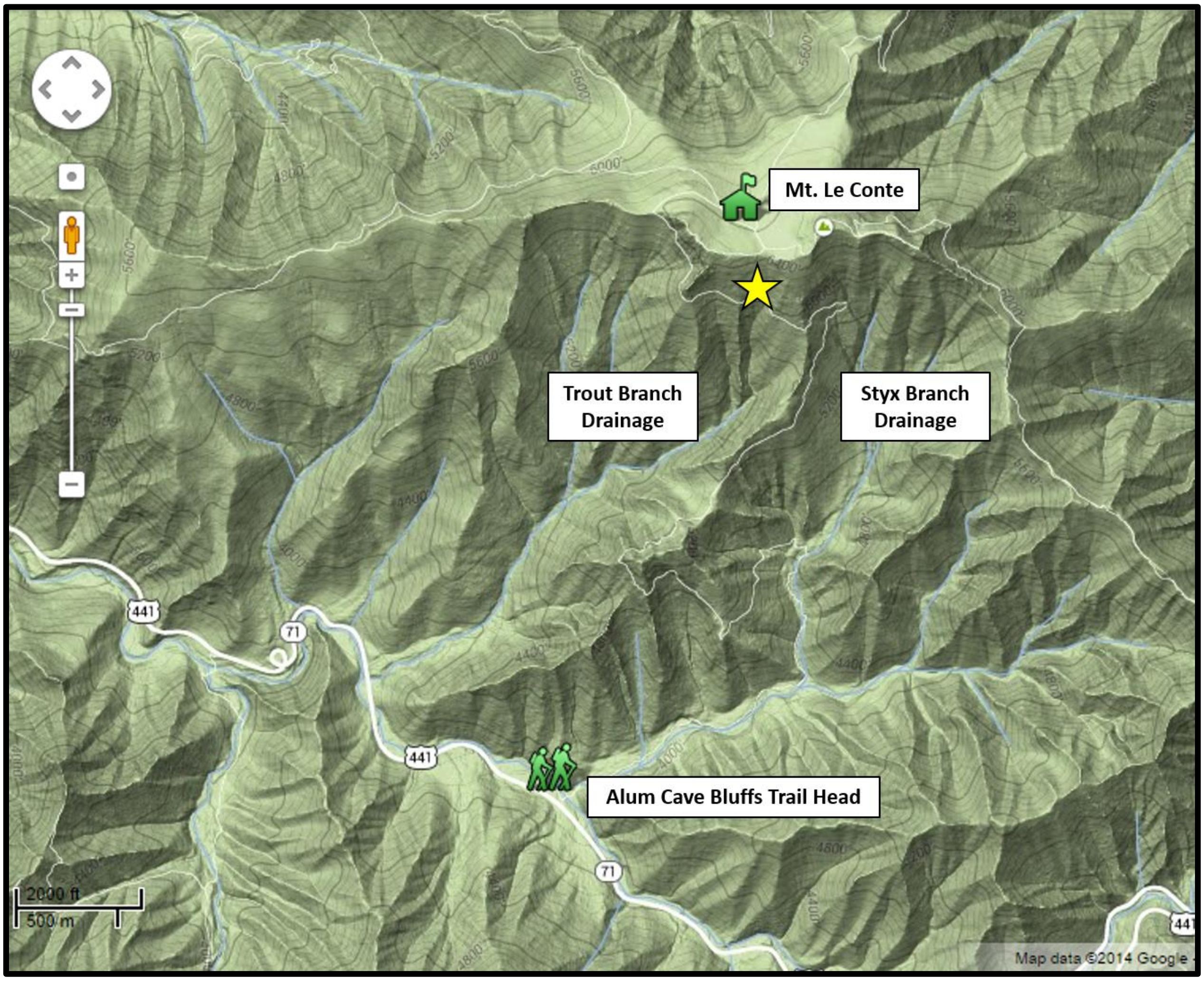


Figure 5.2: Mount Le Conte trail map showing Alum Cave Bluffs Trail used for the study. The main drainages of the study area are labeled. The yellow star indicates the location of LC01. Map provided by Google Maps.

Figure 5.3: Slide head of LC01. Picture shows one half of slide head above the Alum Cave Bluffs trail with circular/crescent-shaped scar and planar slide surface. Main slide scar is covered by Cain's reedgrass and wretched sedge (Photo by Maegen Rochner).

1952 growing season, and 1952 may serve as a test for the application of dendrogeomorphic methods at the site.

LC01 lies on the rust-stained Anakeesta Formation, which includes metasiltstone, phyllite, slate, metasandstone, schist, and dolomite (Hadley and Goldsmith 1963). Much of the Anakeesta formation bedrock on lower portions of the slide remains exposed. The exposure of bedrock initially favors light-tolerant and fast-growing mosses and grasses (Crozier 1984; Ryan 1989), but the establishment of other species, especially trees, is a much slower process. A shorter growing season, combined with steep slopes, harsh climate, and acidic soils, make the regeneration process slow (Schneider 1973; Ryan 1989; Wise and Petersen 1998). At high elevation sites of disturbance, bare rock and talus slopes can remain bare for up to 100 years and are the slowest to recover through secondary succession (Flaccus 1959). Exposed bedrock and continued headward erosion make it harder for red spruce to establish on the steep slopes of the slide head, especially when red spruce regeneration tends to occur in pulses (Pauley 1993). Successful red spruce regeneration is more likely when favorable soil conditions and a regenerative pulse coincide. Time is needed for soil to accumulate to an appropriate level (Feldkamp 1984), and for a reproductive pulse to occur (Pauley 1993). The combination of harsh conditions and proper timing has slowed the re-establishment of red spruce at LC01. In addition, LC01 (1800 m) is located near the spruce-fir line at 1900 m (Whittaker 1956), and Fraser fir is likely hardier at the elevation and the first to re-establish on exposed slopes.

The climate at LC01 is cool and moist because of high elevations, high winds, winter snow, clouds, and heavy rains. In GSMNP, high elevations at mountain peaks (The elevation of Mt. Le Conte is 2010 m) can experience daily temperatures 9–12 °C cooler than at the base, and annual precipitation values over 2000 mm are common (Shanks 1954). As elevation increases and temperature decreases up the mountain, forest type transitions from hardwood to spruce-fir, with red spruce beginning around 1370 m, spruce and fir at 1670 m, and Fraser fir (*Abies fraseri* (Pursh.) Poir) above 1900 m (Whittaker 1956). The LC01 site contains a mixture of tall red spruce trees and smaller Fraser firs. Because the balsam wooly adelgid greatly affected Fraser fir in the southeastern Appalachians (Busing and Pauley 1994), the National Park Service forbids the coring of Fraser fir. This regulation restricted sampling to red spruce.

Understory species at LC01 consist primarily of Catawba rhododendron (*Rhododendron catawbiense* Michx.), spinulose shield fern (*Dryopteris austriaca* var. spinulose (Muell.) Fiori), smooth blackberry (*Rubus canadensis* L.), hobblebush (*Viburnum alnifolium* Marshall), Blueridge blueberry (*Vaccinium pallidum* Aiton), southern mountain cranberry (*Vaccinium erythrocarpum* Michx.), and mountain oxalis (*Oxalis montana* Raf.) (Braun 1950). The main slide area of LC01 is covered by a thick layer of Sphagnum moss and grasses, including Cain's reedgrass (*Calamagrostis cainii* Hitchc.) and wretched sedge (*Carex misera* Buckley) (Feldkamp 1984). The purple-flowered narrowleaf gentian (*Gentiana linearis* Froel.) covers the grassy portion of the slide during the warm months (Feldkamp 1984). Other plants seen at LC01 include Michaux's saxifrage (*Spatularia michauxii* Britton), skunk goldenrod (*Solidago glomerata* Michx.), and Rugel's ragwort (*Rugelia nudicaulis* Shuttlew. ex Chapm.) (Wise and Petersen 1998). Trees on the perimeter of the slide are rooted in very thin soil and surrounded by woody debris. Most trees have exposed roots with cavities underneath (Fig. 5.4) that reveal bedrock on the steep slopes, suggesting that perimeter trees might have survived exposure of their roots by the debris slide.

Such exposure might also be caused by the limited amount of soil on the steep slopes of the Anakeesta formation at high elevations.

5.5 Methods

5.5.1 Field Methods

LC01 was first located using Google Earth to identify slide scars on Mt. Le Conte. In the field, we chose LC01 from a group of debris slide scars based on efficient access and safety and on the existence of red spruce near the slide scar boundaries where it would be most likely to have a disturbance signal. Primary forms of tree-ring evidence used in dendrogeomorphic analysis include growth release due to removal of competition, growth suppression due to scarring or removal/exposure of roots or injury to tree tops by debris, growth of reaction wood due to tilting, or physical injury from debris (Shroder 1980; Stoffel and Bollschweiller 2008 and 2009; Clague 2010). Preliminary investigation of LC01 suggested the potential impact of soil creep, and subsequent growth of reaction wood to correct growth, on trees growing on steep slopes, so we disregarded the tilting of trees as possible evidence at LC01. Trees that experience creep may exhibit reaction wood growth not related to debris slides. Evidence of growth release or suppression in slide perimeter trees was used as the primary indicator of debris slide activity.

To identify a disturbance signal, we chose to sample red spruce trees based on proximity to the main slide area. Trees within 5 m of slide boundaries are most likely to have experienced growth release because of the removal of competition, growth suppression following scarring or removal/exposure of roots or injury to tree tops by debris, or both (Shroder 1980; Stoffel and

Figure 5.4: Exposed roots with cavities underneath of red spruce on LC01. (Photo by Maegen Rochner).

Bollschweiller 2008 and 2009; Clague 2010). Trees chosen for sampling in GSMNP could not be cut down to obtain cross-sections, so sampling was limited to increment cores for obtaining the history of disturbance for the area and for obtaining the data needed to analyze climate-growth relationships in disturbed red spruce. We took core samples using a Haglof 3-thread increment borer.

In addition to trees sampled on or near slide scar boundaries (Fig. 5.5), we also developed a control chronology (Le Conte Reference, LCR) from other red spruce trees on the peak and south face of Mt. Le Conte and near to, but not affected by, the debris slide site (Fig. 5.6) (Fantucci and Sorriso-Valvo 1999). Most of these trees were located near the Alum Cave Bluffs trail and were chosen based on the likelihood of obtaining a reference chronology long enough to match that developed for LC01 and of recording local climate. To ensure a control chronology that best represented the climate signal and was most comparable to the LC01 chronology, we sampled trees within a 400 m elevation range covering both sides of the debris slide site and on the south face of Mt. Le Conte, and did not sample trees showing signs of injury or that were near a gap. We used LCR to create a difference chronology (comparison of a disturbed chronology with a control) and this aided in the isolation of debris slide events from suppression and release sequences caused by local climate variables. This method is more thoroughly discussed in the following section.

Figure 5.5: LC01 site with mature trees along the edges of the slide scar (Photo by Maegen Rochner).

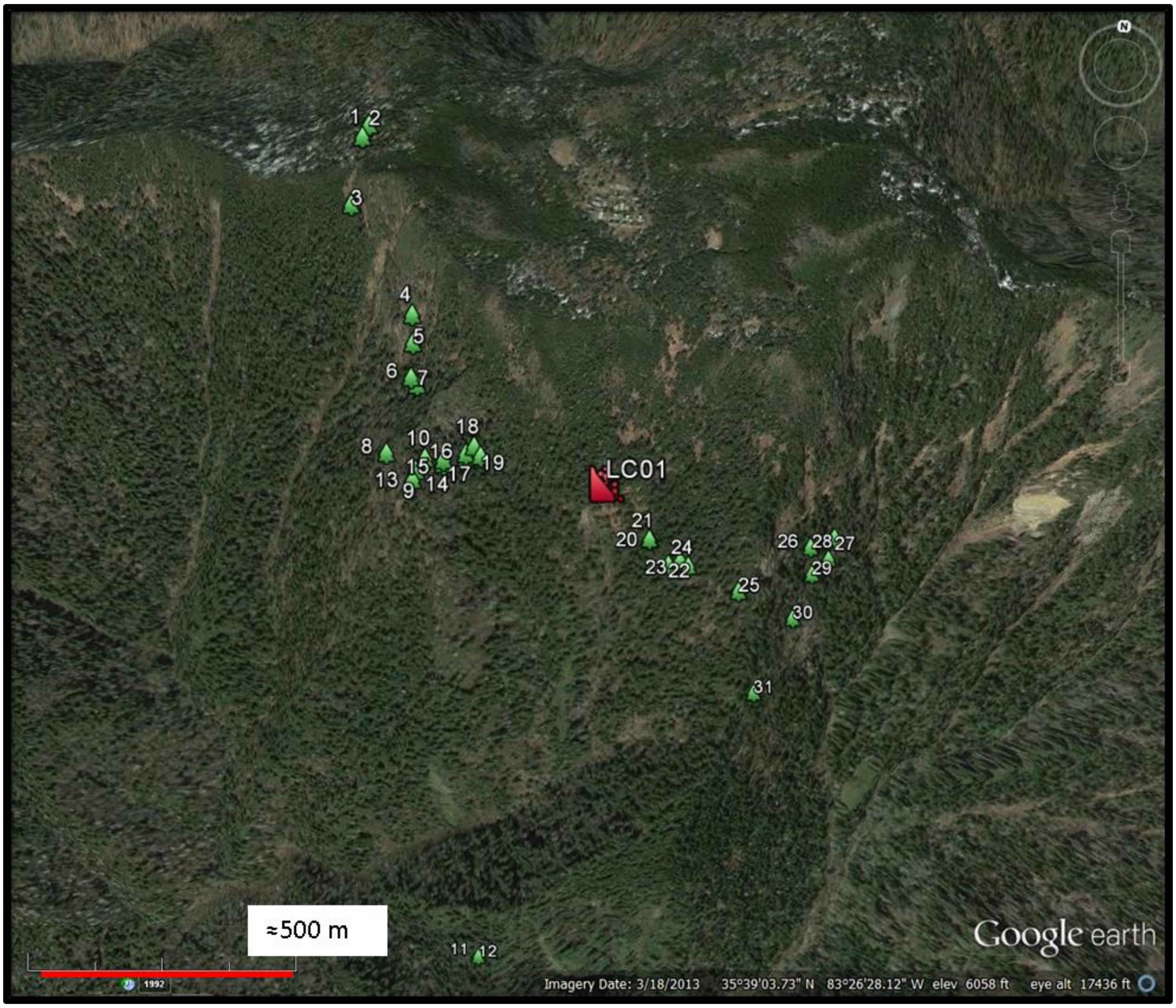


Figure 5.6: Google Earth image showing red spruce trees sampled for the control chronology.

5.5.2 Laboratory Methods

5.5.2.1 Chronology Development

We sanded all cores with a belt sander using progressively finer sandpaper, beginning with ANSI 80-grit (177–210 μm) and finishing with ANSI 400-grit (20.6–23.6 μm) to increase visibility and accuracy when measuring ring widths (Orvis and Grissino-Mayer 2002). Once sanded, we marked tree rings using the standard decadal dot notation, starting at the outermost complete ring and counting towards pith (Stokes and Smiley 1996; Speer 2010). All samples were taken from living trees so the date of the outermost ring was known. Counting inward from bark, we dated all rings and the year of the innermost complete ring noted for measuring. We measured total ring widths to 0.001 mm accuracy, starting with the innermost complete ring, using a Velmex measuring system and MEASURE J2X software.

We internally crossdated all measured series using COFECHA (Holmes 1983; Grissino-Mayer 2001) to properly place each series in the correct temporal alignment with the other series. A correlation threshold of 0.40 is used in the Southeastern US (International Tree-Ring Data Bank (ITDRB) 2013) to ensure correct crossdating. Segments analyzed were 40 years in length lagged by 20 years, and the critical correlation for segments was 0.37 (Grissino-Mayer 2001). Internal crossdating is necessary to determine the date of the final ring and to identify missing rings. We used the presence of latewood-earlywood to determine the last possible complete ring because trees were sampled during and after the 2013 growing season. We developed the final raw chronology for the LC01 site using the program ARSTAN (Cook 1985).

5.5.2.2 Climate-Growth Analysis

Before we attempted to identify debris slide events, climate-growth relationships in the tested trees had to be evaluated, and any climate influences that were found had to be subsequently removed. We performed climate response analysis using DendroClim2002 (Biondi and Waikul 2004). We obtained instrumental climate data for monthly average temperature (MNTM), total monthly precipitation (TPCP), and monthly Palmer Drought Severity Index (PDSI) from the National Climatic Data Center (NCDC) divisional data for Eastern Tennessee (NCDC 2014). We used split-data correlation analysis to test for relationships between individual climate variables and standardized tree-ring indices in a chronology and used forward evolutionary analysis to detect changes in climate-growth relationships or in the strength of relationships over time (White 2013). Consistent relationships over time indicate temporal stability, but frequently changing or reversing relationships over time indicate temporal instability.

We tested the climate variables MNTM, TPCP, and PDSI for the period extending from April of the previous year to October of the current year to include the lagged effect of influences from previous years on current year growth. Forward evolutionary analysis tested the common period 1896–2013 and used a baselength interval of 38 years, twice the number of monthly climate variables (19 months each for MNTM, TPCP, and PDSI). In forward evolutionary analysis, the start year of the interval remains fixed and, for each test, the end year is increased by one. Intervals then move forward in time through the tested period, adding one year at a time while the first year remains fixed. Results from forward evolutionary analysis covered the period 1933–2013. In addition to individual monthly climate variables, we also tested seasonal combinations of variables based on patterns seen in the detrending method tests. Seasonal variables tested were summer temperature (June-August), winter temperature (January-March), spring precipitation (April and May), summer precipitation (July and August), and fall PDSI values (August-November).

5.5.2.3 Disturbance

We performed disturbance analysis using raw ring-width data instead of the standardized chronology used in climate-growth analysis. Once properly dated, we transformed raw ring-width series to column format using YUX software so that raw measurements could be graphed using Microsoft Excel. We scanned these graphs and the cores and compared them for a visual determination of suppression and release sequences, as well as identification of possible callus tissue from scarring or reaction wood from tilting (Stoffel and Bollschweiler 2008). We used JOLTS (Holmes 1999) software to objectively identify suppression and release sequences within each core and the combined series using a 10-year moving average to locate instances of sudden and then continued release or suppression events (Cseke 2003; Brose *et al*. 2010; White *et al.* 2012). The JOLTS reported mean release factor (MRF) is the magnitude of release compared to the previous 10 years' growth and may aid in the determination of significant event years. MRF values for debris slide event years should be high (Cseke 2003). We set JOLTS parameters with a running mean window ten years prior to tested years and two years starting at the tested year. The release factor sets the desired magnitude of release or suppression, and we set this at two, or a 200% increase or decrease in growth from the previous year. We set the minimum number of years between detected releases to 10. Dates flagged for suppression or release could possibly be identified as dates for the LC01 debris slide events, but such years must be noted in a majority of the trees to count as evidence for a significant mass movement event. Any release or suppression caused by a climate factor must also be ruled out.

We used the index percentage introduced by Shroder (1978) to determine the significance of identified disturbances. Index percentages, or the percent of trees affected by a mass movement based on living trees sampled in that year, can be graphed temporally to identify peaks in disturbance. For this study, we chose an arbitrary threshold of 10% based on trends seen in graphed results from LC01 (Fig. 4.1). If more than 10% of living trees sampled for one year showed the onset of suppression or release, we listed these years as possible debris slide dates (Table 4.2). However, we could not identify these dates as debris slide dates until any climate-growth response in the sampled red spruce had been removed.

5.5.2.4 Removing Climate

The primary method used to remove climate signal from the chronology was comparison with a control chronology, visually and using the difference chronology, performed in OUTBREAK (Slayton 2010). A difference chronology uses a local reference, or control chronology, and compares (or subtracts from it) the disturbed chronology. Where the two chronologies are the same, the trees are understood to have been affected by the same climate influences. However, where the chronologies show a difference, something has affected the disturbed chronology and not the control. OUTBREAK detects insect outbreaks by comparing a non-host chronology (control) with a host chronology (disturbed). OUTBREAK corrects the host-tree chronology by first scaling the non-host chronology to the same variance as the host, producing scaled residuals. These scaled residuals equal the predicted residual indices (PRI). The indices are given in a corrected chronology with a mean of one. The lowest indices (suppressions) represent reduced growth in the host chronology but not the non-host, therefore the outbreaks (Swetnam *et al*. 1985; Zhang and Alfaro 2003). For this study, we treated the disturbed chronology at LC01 as the host chronology, with outbreaks being debris slide events instead of insects (Slayton 2010). Default parameters for OUTBREAK were used (see Appendix 5).

Crossdating affected trees with a local reference chronology can help rule out confounding factors (Hupp *et al.* 1987; Schweingruber *et al*. 1990). For this study, we needed to remove climate from the disturbed chronology to determine which suppression or release sequences were caused by debris slides and not by any climate event. Trees near to, but not affected by the slide will have experienced the same climate events as the sampled trees near slide scar boundaries. For the difference chronology, we sampled 30 red spruce trees on the peak and south face of Mt. Le Conte, making sure not to collect any trees close enough to the debris slide scar to have been affected by the canopy opening. We prepared the samples and crossdated using COFECHA (Holmes 1983; Grissino-Mayer 2001), and held the LCR chronology to the same standards as the disturbance chronology (see *5.3.2.1*). If the control chronology (LCR) indicated suppression or release sequences also seen in the disturbed chronology, these were not considered to be evidence of the debris slide but of some other phenomenon, most likely climate. In addition to the control chronology from Mt. Le Conte, we also compared the disturbed chronology to a red spruce chronology developed for Clingman's

Dome (ITRDB NC002), another high-elevation red spruce site in GSMNP at N 35.6 W 83.43, approximately 11 km from Mt. Le Conte. The Clingman's Dome chronology (NC002), collected by E. R. Cook, covers the period 1558 to 1983. Because of the distance between LC01 and Clingman's Dome, and lack of ring width data for 1984–2013, we did not expect growth patterns to match as well with NC002 as with the LCR chronology.

We continued procedures to remove climate influence using exploratory methods. We also used regression modelling of tree growth, based on climate-growth relationships, to remove climate influences (Cook *et al*. 1987; Grissino-Mayer and Fritts 1995; Speer 2001). We used multivariate linear regression to model tree growth (dependent variable) using climate variables (independent variables). We tested climate variables individually, starting with those that had shown the strongest climate-growth relationship and working downward through the ten most significant climate influences found in climate-growth analysis. We documented the significance of each regression model with the F-statistic and its corresponding p-value, with the F-value goal of $p \leq 0.05$ significance. The r^2 statistic from each significant model represented the percentage of tree growth explained by the climate variable used in the regression. For example, a significant model with an r^2 value of 0.08 meant that the climate variable represented 8% of tree growth. After the first climate-growth regression was performed, the resulting residuals (the difference between actual and expected/modelled growth) represented tree growth with the influence of that climate variable removed. We then regressed these residuals with the next most influential climate variable in a second model. We continued this process with the rest of the ten climate variables until models were found to be insignificant based on F-values. The final set of residuals produced was graphed as the final residual chronology with significant climate variables removed. With each successional climate variable regressed and removed, we added r^2 values together to represent the total percentage of climate influence removed, with the goal of removing 25–30% (considered the average amount accounted for by climate in tree-ring data for southeastern conifer trees) (Coile 1936; Cook *et al*. 1988; Grissino-Mayer *et al*. 1989; Grissino-Mayer and Butler 1993; Cook *et al*. 1999; DeWeese *et al*. 2010). We added r^2 values together to represent total climate influence under the assumption that the climate variables used in the model are independent of each other, an assumption common in the use of this method in dendrochronology.

One way to visualize this method is to envision a tree ring. Each significant model will explain a percentage of growth seen in that tree ring. The first model, say summer precipitation, might explain 8% of the width of that tree ring. The next model, say summer temperature, might explain another 8% of the tree ring width. This totals to 16% of growth explained by summer precipitation and temperature. The residuals from these models (actual minus predicted growth) represent tree growth with this 16% influence removed. The final goal is to remove the influence of climate on ring width and better isolate the influence of other factors, in this case growth suppression or release caused by debris slides. If suppression or release sequences originally seen in the disturbance chronology persist despite the removal of the strongest climate influences, they are more likely to have been caused by the debris slide and not by a climate variable. However, if the influence of climate proves to be small, this may not be the case.

The final exploratory method that we used was the comparison of possible event dates with local climate data. We graphed east Tennessee divisional climate data and compared the graphs with suppression and releases seen in the raw ring-width data collected from LC01. We used this comparison to identify possible droughts or changes in temperature that might have caused changes in red spruce growth. However, instances of high rainfall that corresponded with changes in growth could also be considered triggers of a debris slide event, especially if high rainfall corresponded with any sudden growth suppression.

5.6 Results

5.6.1 Chronology Development

The final raw LC01 chronology (Fig. 5.7) covered the period 1792–2013 and consisted of 59 dated tree-ring series from 34 individual red spruce trees. Any possible debris slide dates from dendrogeomorphic analysis therefore, can only go back to 1792. The mean segment length was 149.6 years. The interseries correlation was 0.53 ($p \leq 0.0001$), which is exceptionally high for southeastern trees. The interseries correlation was above the critical threshold of 0.40 for southeastern trees (ITRDB 2014a) and slightly below the average (0.56) for red spruce, species code PCRU (ITRDB 2014b). The mean sensitivity was 0.20, slightly below the average (0.22) for red spruce (ITRDB 2014b). Mean sensitivity measures changes in year to year ring width, with high values indicating higher sensitivity to climate variables. Values vary from high for drought-sensitive conifers (0.65) to low for complacent trees (0.15) that experience few limiting factors in favorable environments (ITRDB 2014b). In the southeastern U.S., a minimum mean sensitivity of 0.20 is typically required to indicate the climate sensitivity needed for crossdating.

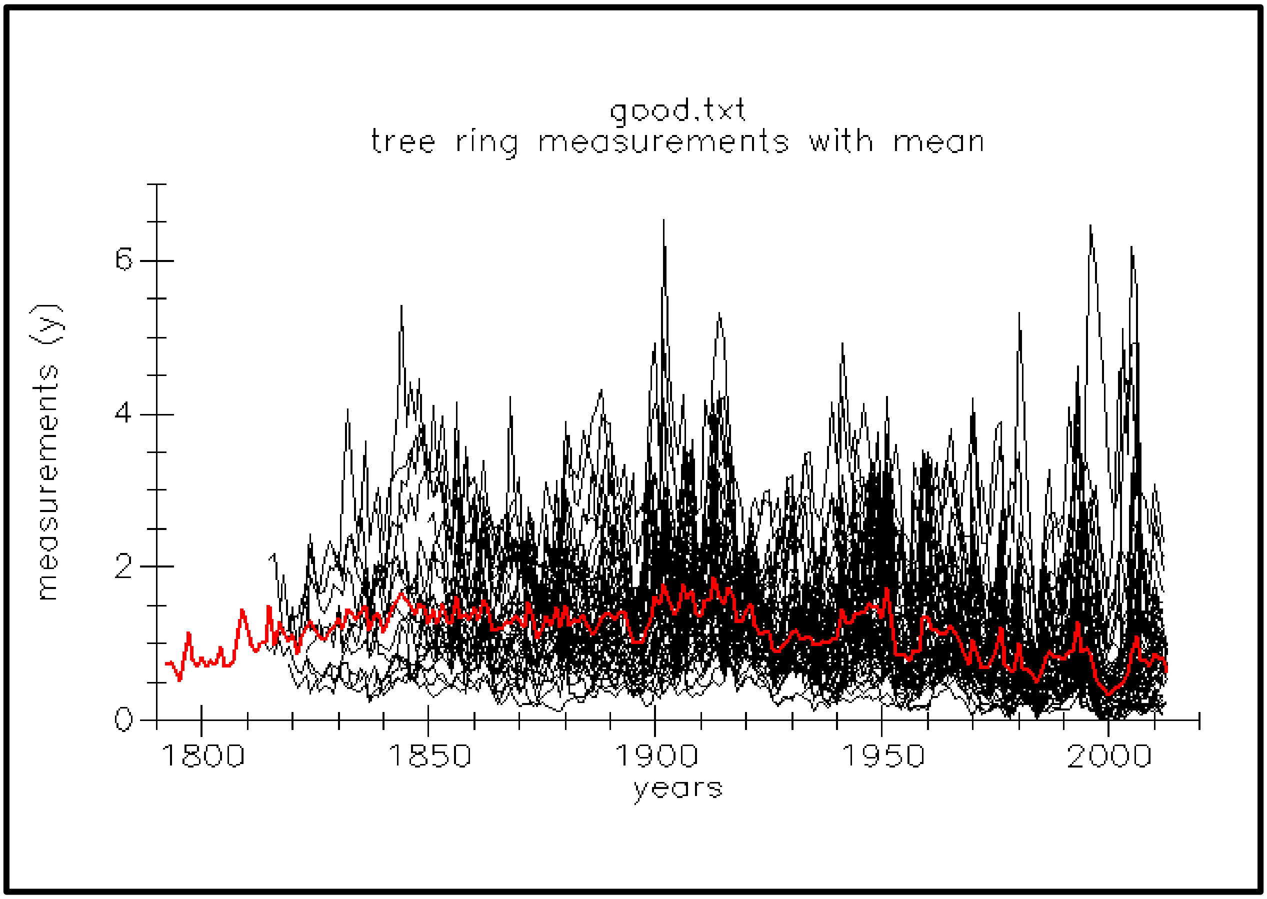


Figure 5.7: Raw LC01 chronology (red) produced by ARSTAN (Cook 1985) averaging values of 59 series.

5.6.2 Climate-Growth Analysis

The strongest relationship for both temperature and precipitation (found using a 15-year spline detrended chronology) was with previous August precipitation ($r = 0.31$, $p \leq 0.05$) (Fig. 4.4). Other strong relationships included current March temperature ($r = –0.22$, $p \leq 0.05$), current May precipitation ($r = –0.22$, $p \leq 0.05$), current July temperatures ($r = 0.24$, $p \leq 0.05$), and previous August, September, and October PDSI ($r = 0.26$, 0.22, 0.25, $p \leq 0.05$ respectively). Four of the five tested seasonal variables had significant ($p \leq 0.05$) relationships with growth in red spruce: previous summer precipitation ($r = 0.21$), previous fall PDSI ($r = 0.25$), current summer temperatures ($r = 0.21$), and current spring precipitation ($r = –0.30$).

Forward evolutionary analysis revealed temporally stable relationships between red spruce growth and both temperature and precipitation variables. The red spruce growth relationship with current July temperatures was temporally stable through most of the tested 117-year period (1896–2013), except when the years 1976–1983 were added, which resulted in correlations below 0.20. A relationship with current January temperature remained stable up to the 1970s, and a weaker relationship with current March temperatures emerged after the 1960s. Relationships with precipitation revealed a higher level of temporal stability, especially with current April precipitation, which remained strong and stable until near the end of the tested period or until the late 2000s. A relationship with current May precipitation was stable but weaker beginning around 1950. The strongest climate variable relationship revealed through correlation analysis, previous August precipitation, was stable after 1950, with pockets of strong correlation periods in earlier years. A positive relationship with previous May precipitation weakened in the 1970s. No PDSI relationship was found to be temporally stable. A weaker but stable relationship with previous October PDSI emerged in the 1950s.

The influence of climate on red spruce growth at LC01 was found to be significant, but low correlation values of no greater than 0.31 indicated that the overall effect of climate is not strong. Climate variables may only explain a small percentage of growth. However, the significant influence of climate prompted us to remove this influence before creating a debris slide history for LC01.

5.6.3 Disturbance History

Preliminary visual analysis of the cores and raw ring width graphs created with YUX software provided evidence of 13 disturbance events that affected > 10% of total sampled trees and of five events that affected > 20% (Fig. 5.8 and Table 5.1). However, many of these dates were clustered within eight possible ranges for disturbance event dates (Table 5.1). We combined data for years that showed opposing evidence (suppression and release in different trees) to give the total number of trees affected per year. Opposing responses are more likely to indicate debris slides because climate would be less likely to initiate opposing responses in neighboring trees (Cseke 2003). The primary events (Fig. 5.8 and Table 5.1) occurred during the years 1952–1953 (Fig. 5.9) and 1996–1998. The 1952–1953 event corresponds with the September 1, 1951 cloudburst event (Bogucki 1970), which would have affected trees during the following growing season, 1952. Also of note was the reoccurrence of wide rings in 1951 (the year of the cloudburst and year before suppression) and 1993 (before a suppression in 1996 and year of slide-producing summer storm in GSMNP). The 1996–1998 event led to a sustained

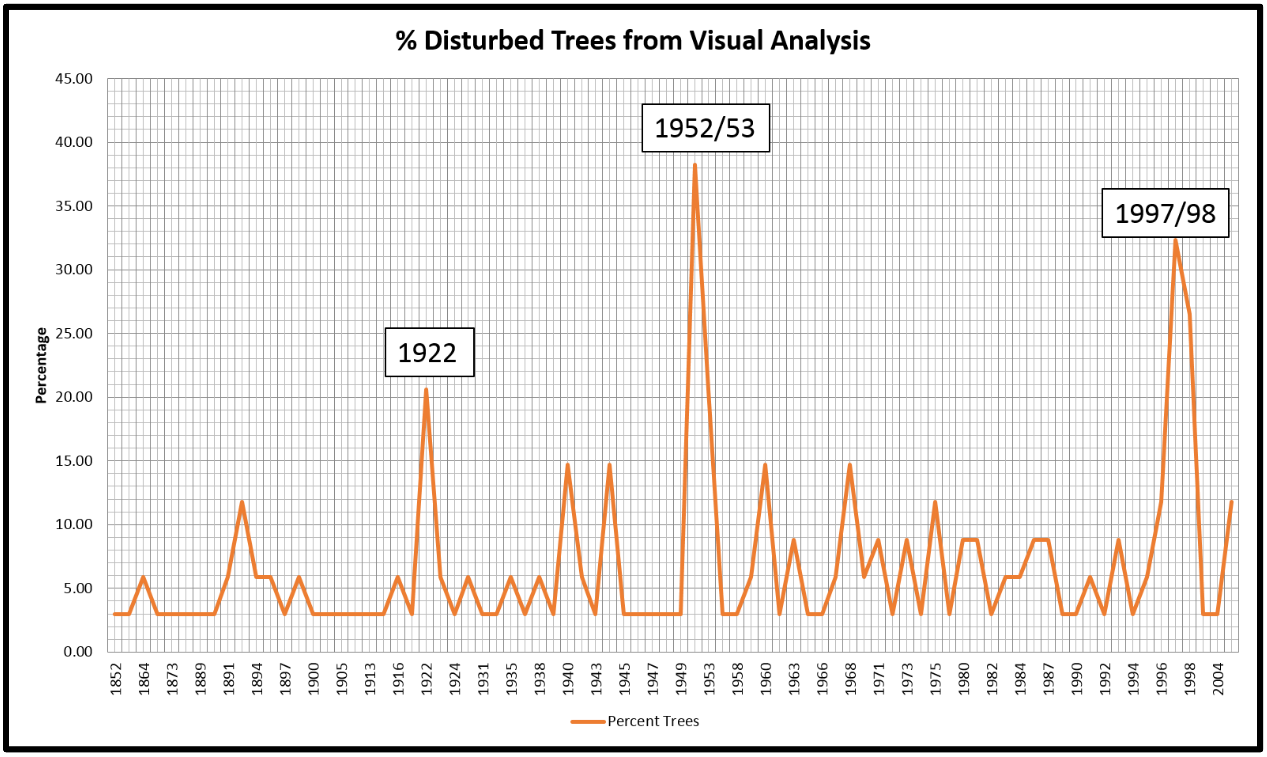


Figure 5.8: Graph of disturbance events (suppression and release combined) based on identification in visual analysis. Five dates were found in more than 20% of trees but represented only three events.

Table 5.1: Dates of possible event dates developed from visual analysis of LC01 cores and from line graphs of raw ring widths.

Visual Analysis Results			
	Response		
Year	Suppression	Release	% Trees
1893	4	X	12
1922	7	X	21
1940	1	4	15
1944	X	5	15
1952	13	X	38
1953	7	X	21
1960	1	4	15
1968	4	1	15
1975	1	3	12
1996	3	1	12
1997	11	X	32
1998	9	X	26
2005	X	4	12

Clusters			
Years	Response	# Trees	% Trees
1891-1894	S	8	24
1919-1923	S	10	29
1940-1944	S and R	13	38
1952-1953	S	20	59
1959-1960	S and R	7	21
1967-1969	S and R	9	26
1981-1984	S	8	24
1996-1998	S and R	24	71

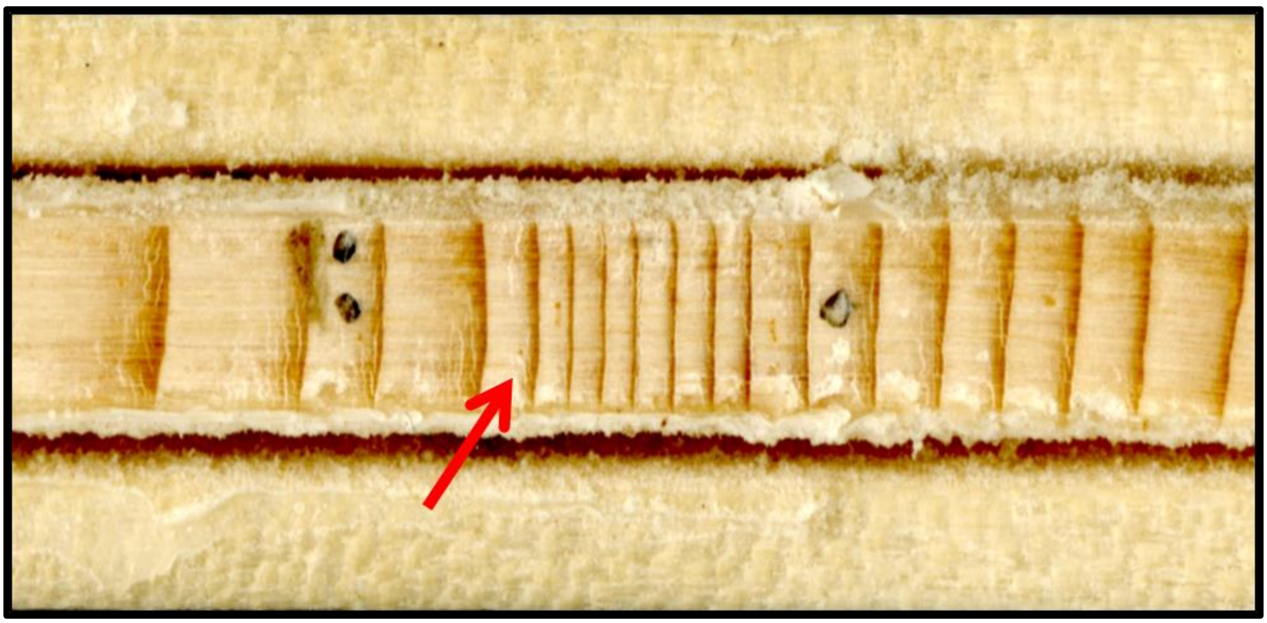


Figure 5.9: Red spruce core LC01-2E showing the 1952 suppression followed by a release/recovery in 1959.

suppression and missing rings in many trees. The suppression lasted until a 2005–2006 release event (seen in more than 10% total trees) (Fig. 5.10) but cannot be confirmed as a debris slide date until climate has been ruled out.

Initial disturbance analysis, prior to climate signal removal, in JOLTS (Holmes 1999) provided a list of possible event dates and indicated that the overall environment experienced frequent disturbance throughout the chronology (Fig. 5.11). Event dates exceeding the 10% index were chosen as probable debris slide dates and included: 1825, 1836, 1858, 1909, 1918, and 1952 (suppression) and 1959, 1975, 1986, 1992, and 2005 (release) (Table 5.2). Two event years found during initial visual inspection and supported by JOLTS results (greater than 20% index) were 1952 (20.60%) and 2005 (38.24%). Once again, the 1951 cloudburst event was indicated by a suppression period beginning in 1952. Other dates found during the initial visual inspection and supported by JOLTS results included 1959–1960 (11.76%) and 1975 (11.76%). The 1959–1960 release event was seen visually in seven trees (20.588%) and supported by an 11.76% index calculated with JOLTS results. It may indicate a recovery event following the 1952 suppression. After the removal of climate and a comparison with weather station data, the possible event dates listed from visual and statistical analysis were either accepted or rejected.

5.6.4 Removing Climate

The final Le Conte reference chronology (LCR) (Fig. 5.12) covered the period 1698–2013 and consisted of 27 dated tree-ring series from 26 individual red spruce trees sampled from the peak and south face of Mt. Le Conte. Five trees were not used due to complacency in tree rings

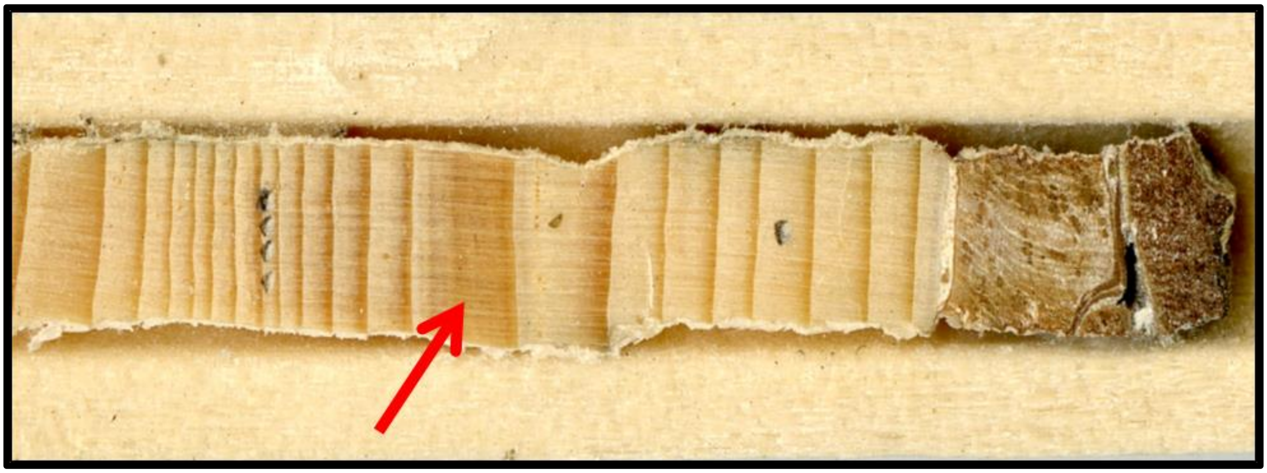


Figure 5.10: Red spruce core LC01-22 showing wide rings/release in 2005–2006.

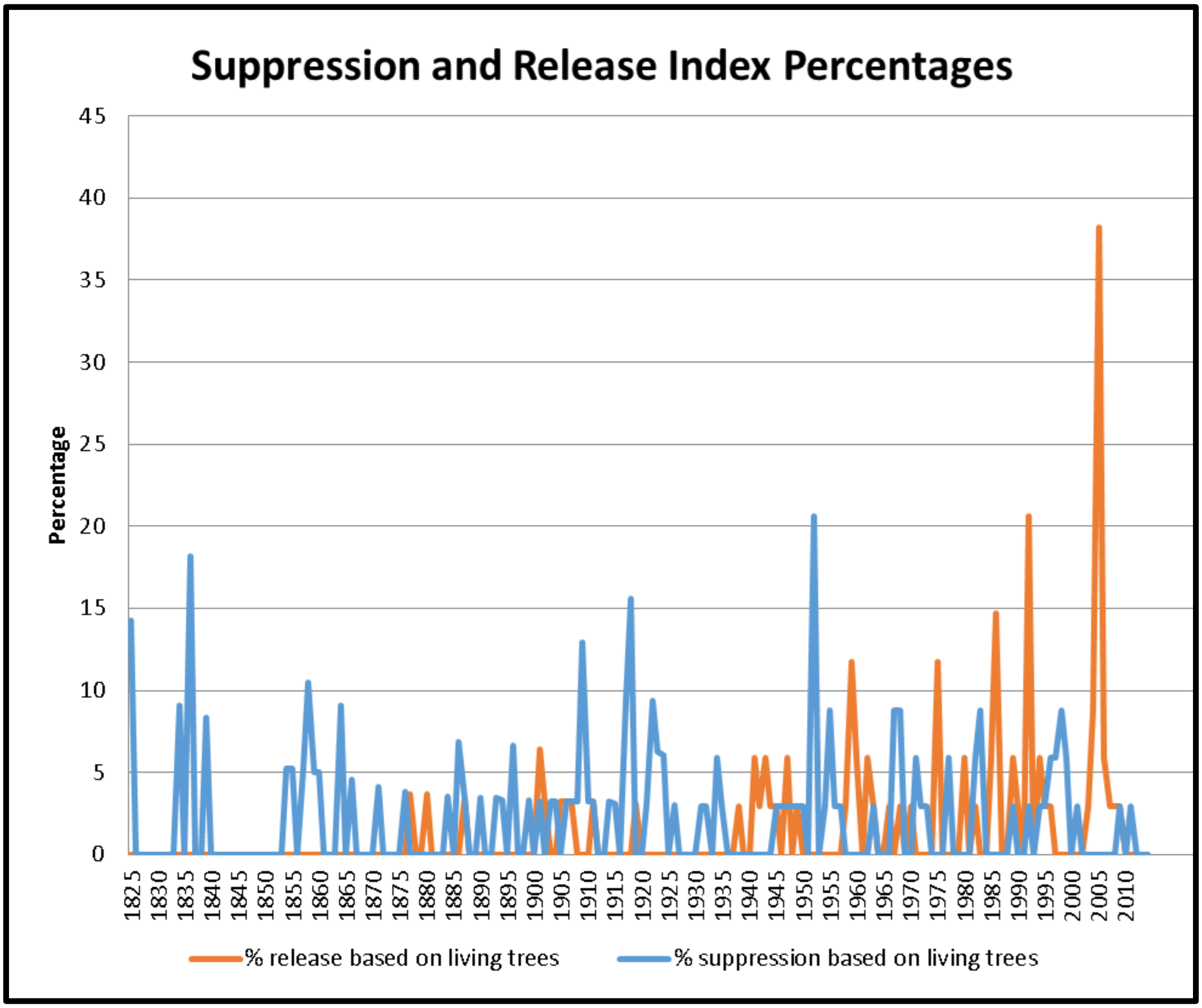


Figure 5.11: Percentages of trees showing suppression and release onset dates based on results from JOLTS software analysis. Percentages are based on the number of trees sampled alive in the event year (The index percentage introduced by Shroder 1978). Blue lines indicate suppression; red lines indicate release sequences. Event dates with percentages exceeding 10% of living trees sampled were identified as possible debris slide years but required further study.

Table 5.2: Table of estimated event dates from those dates exceeding index percentage of 10% of living trees sampled for that year recording the event: suppression (S) or release (R). Event years for initiation of suppression or release provided by JOLTS results.

Estimated Event Dates						
Onset Year	**R**	**Living Trees**	**Index %**	**S**	**Living Trees**	**Index %**
1825	0	7	0.00	1	7	14.29
1836	0	11	0.00	2	11	18.18
1858	0	19	0.00	2	19	10.53
1909	0	31	0.00	4	31	12.90
1918	0	32	0.00	5	32	15.63
1952	0	34	0.00	7	34	20.59
1959	4	34	11.76	0	34	0.00
1975	4	34	11.76	0	34	0.00
1986	5	34	14.71	0	34	0.00
1992	7	34	20.59	1	34	2.94
2005	13	34	38.24	0	34	0.00

and the inability to internally crossdate corresponding series. The mean segment length was 198.0 years. The interseries correlation was 0.51 ($p \leq 0.01$), which is high for southeastern trees and above the critical threshold of 0.40 for southeastern trees (ITRDB 2014a) and below the red spruce average of 0.56 (ITRDB 2014b). The mean sensitivity was 0.20, indicating complacency in tree ring growth in the sampled red spruce trees. This proved to be a complication in crossdating tree ring series for the control chronology and strengthened findings which indicated climate is not limiting at LC01.

Difference chronologies in OUTBREAK indicated possible debris slide events during the periods 1792–1795, 1814–1841, 1885–1888, 1955–1968, 1971–1983 (compared to the Clingman's Dome Chronology), and 1793–1807, 1825–1840, 1907–1910, 1952–1969 (compared to the Le Conte Control Chronology) (Fig. 5.13 and 5.14). Dates that corresponded with suppressions seen in visual and JOLTS analyses included 1814–1841, 1825–1840, 1907–1910, and 1952–1969. Visual comparison of the LC01 disturbed chronology and the LCR control chronology narrowed possible dates down even more to 1909 (in the 1907–1910 suppression) and 1952 (Fig. 5.15 and Table 5.3). Another possible suppression was also identified in 1981, an event only identified in one of the clusters identified in visual analysis (Table 5.1). Both LCR and LC01 showed a period of decreased growth in the 1950s, but that at LC01 was more dramatic, indicating that a climate influence decreased growth simultaneously with suppression caused by debris slide stress, and enhanced the overall suppression. Because a 1951 cloudburst was known, we did not reject the 1952 event. Following comparison with the control chronology,

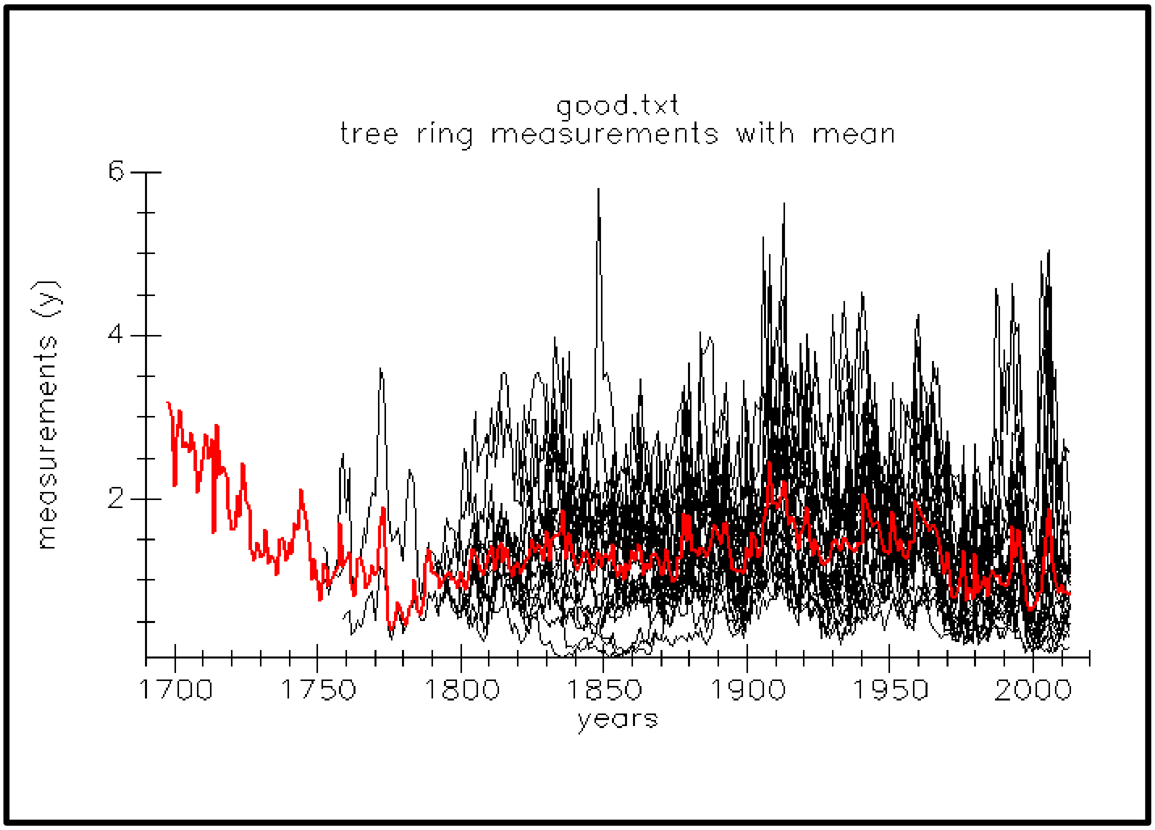


Figure 5.12: Final Le Conte reference chronology (LCR) developed in ARSTAN (red) as a control chronology for comparison with the LC01 disturbed chronology.

we rejected all possible event dates listed from both visual and statistical (JOLTS) results (Table 5.3) as debris slide dates except 1909, 1952, and 1981.

To see if a smaller event, such as a rock fall or small reactivation, may have occurred in the area, we investigated the 1909 and 1981 growth suppressions using Google Earth. We expanded the JOLTS dating of events to include the period 1907–1910 and 1981–1984 for spatial analysis. The 1909 event was not seen in visual analysis but was indicated in JOLTS analysis in six trees. However, no spatial pattern was seen for this event (Fig. 5.16). The 1981 event was identified in visual analysis (three trees) but did not meet the 10% threshold. However, when we expanded the period to include 1982–1984 (as in the cluster used in visual analysis), the number was increased to eight and did meet the 10% threshold. The 1981 date was not identified in the initial JOLTS analysis but, when we expanded the period to include 1982 and 1983, was identified in an additional three trees, making 11 trees in total, recording the 1981 event. These trees were more clustered and followed a line along the central of the three slide sections studied (Fig. 5.17), indicating that the 1981 event may have been a smaller reactivation or rock fall event concentrated in the central slide section. We also checked the 1909 and 1981 dates in the NOAA storm events database to see if heavy rainfall or wind events might correspond with possible debris slide dates. Due to the limited nature of records, 1909 could not be checked. We found one event that preceded the 1981 date: a thunderstorm on September 1, 1980 that was reported to have caused rain and wind damage and power outages (NCDC Storm Events Database 2014). However, this event could not be firmly supported as a slide trigger as no high rainfall amounts or cloudbursts associated with this storm were reported. A

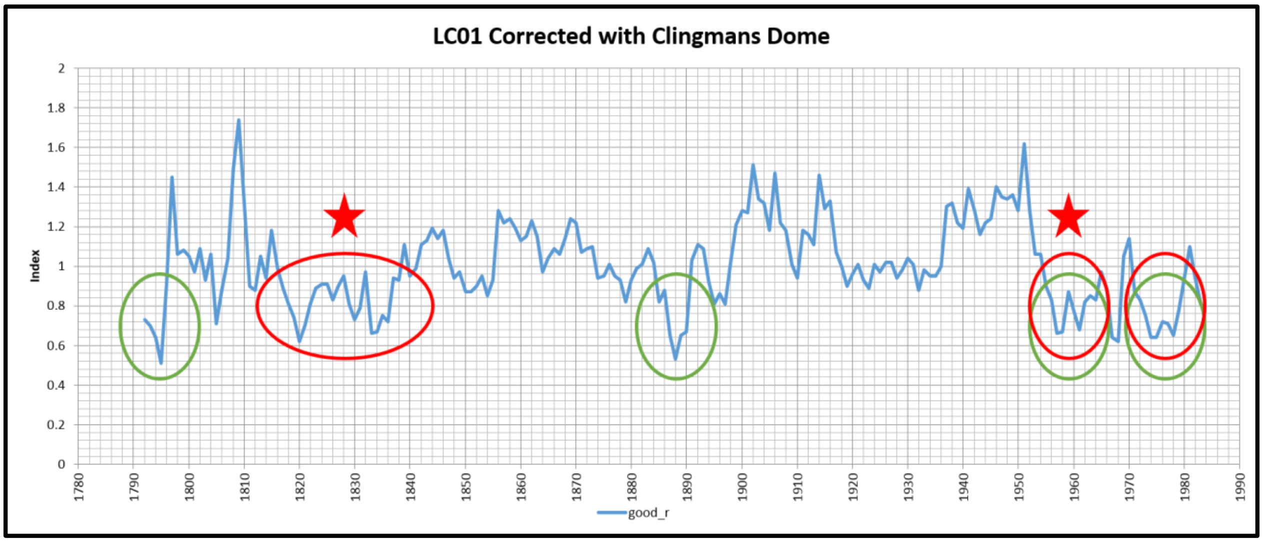


Figure 5.13: Corrected chronology produced by OUTBREAK difference chronology between nc002_crn (Clingman's Dome) and LC01 disturbed chronology. Corrected chronology is given as an index chronology with a mean of one. Lowest indices represent outbreaks (debris slides). Red circles indicate suppression by Budworm and green by Tussock bug species but indicative of a suppression noted in the LC01 chronology but not the Clingman's chronology, or a possible debris slide event. Red circle suppression: 1814–1841, 1955–1968, 1971–1983. Green circle suppression: 1792–1795, 1885–1888, 1955–1958, 1971–1974. Stars indicate suppressions that correspond with JOLTS and visual disturbance analysis.

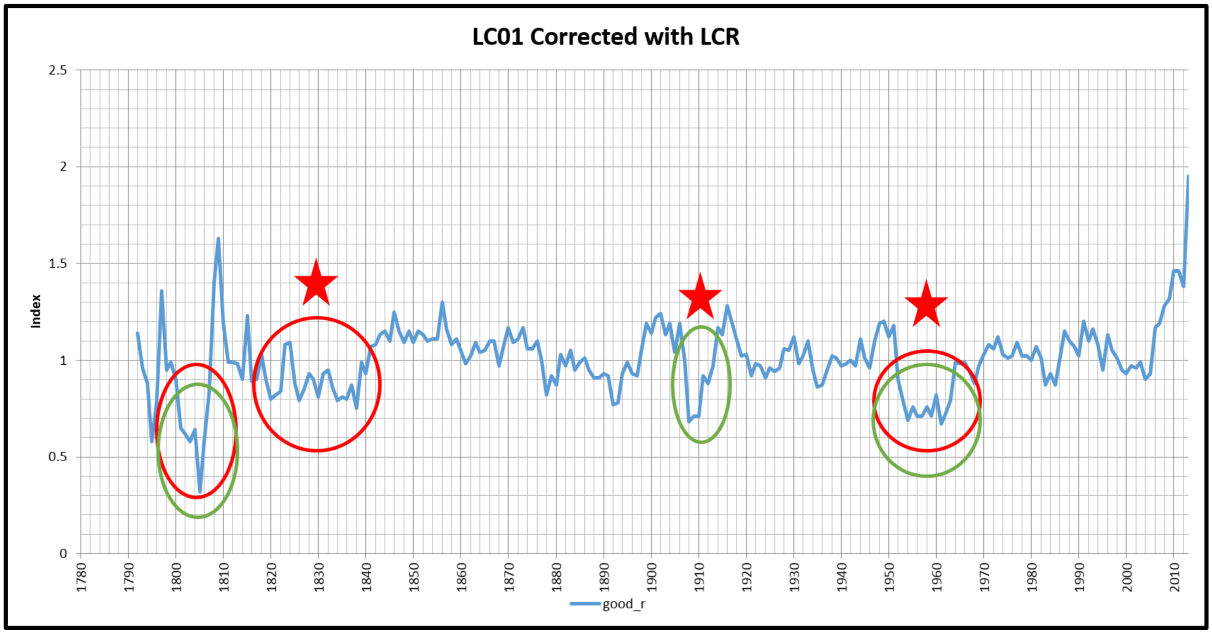


Figure 5.14: Corrected chronology produced by OUTBREAK difference chronology between LCR (Le Conte Reference) and LC01 disturbed chronology. Corrected chronology is given as an index chronology with a mean of one. Lowest indices represent outbreaks (debris slides). Red circles indicate suppression by Budworm and green by Tussock bug species but indicative of a suppression noted in the LC01 chronology but not the Le Conte control chronology, or a possible debris slide event. Red circle suppression: 1793–1807, 1825–1840, 1952–1969. Green circle suppression: 1793–1796, 1798–1801, 1907–1910, 1952–1955. Stars indicate suppressions that correspond with JOLTS and visual disturbance analysis.

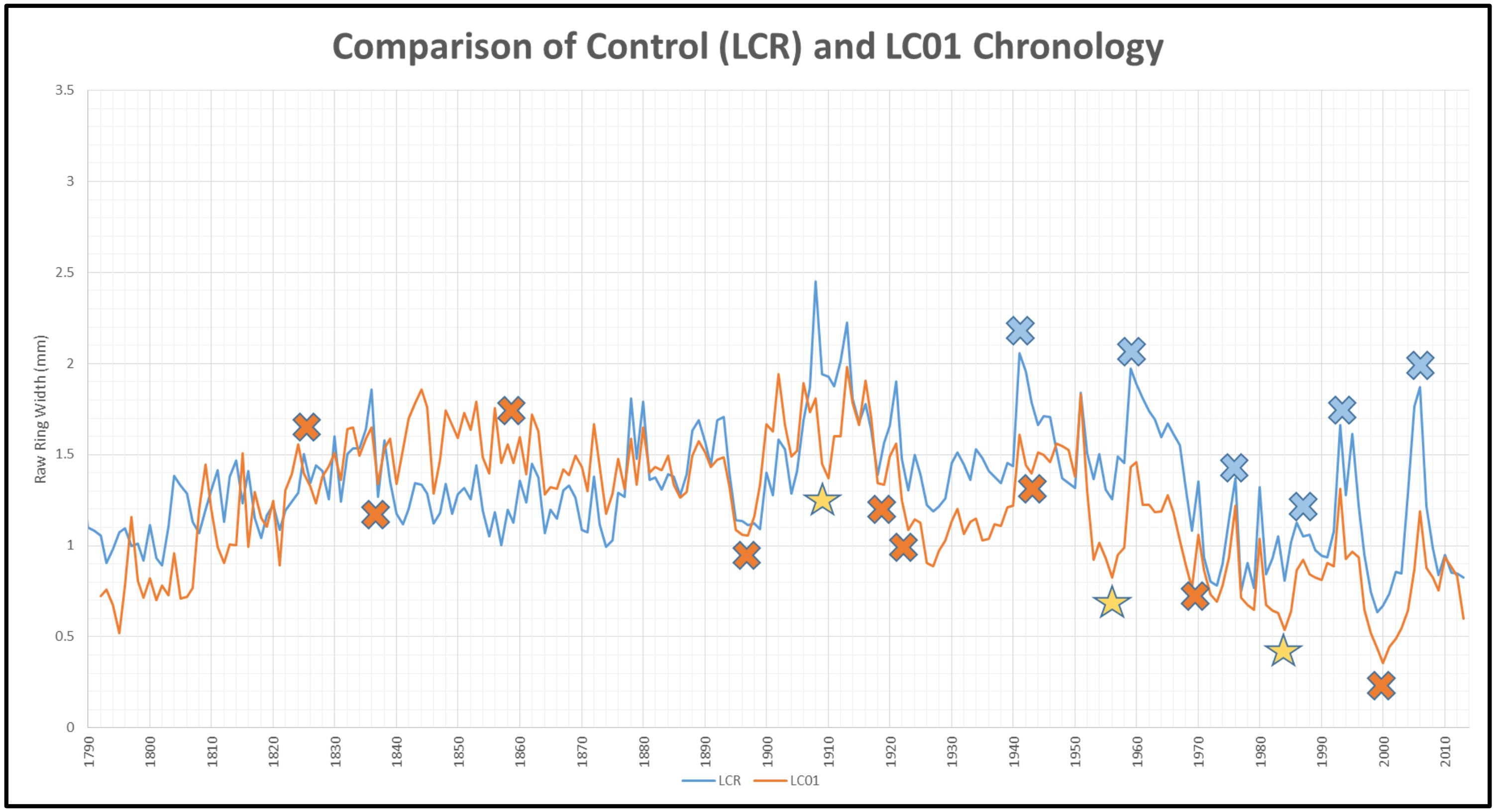


Figure 5.15: Line graph comparison of the control chronology (LCR) with the disturbed chronology (LC01). X indicates estimated event dates from visual and statistical analysis rejected through this comparison. Red X indicates suppression and blue X release. Yellow stars indicate maintained possible debris slide dates (all three suppression).

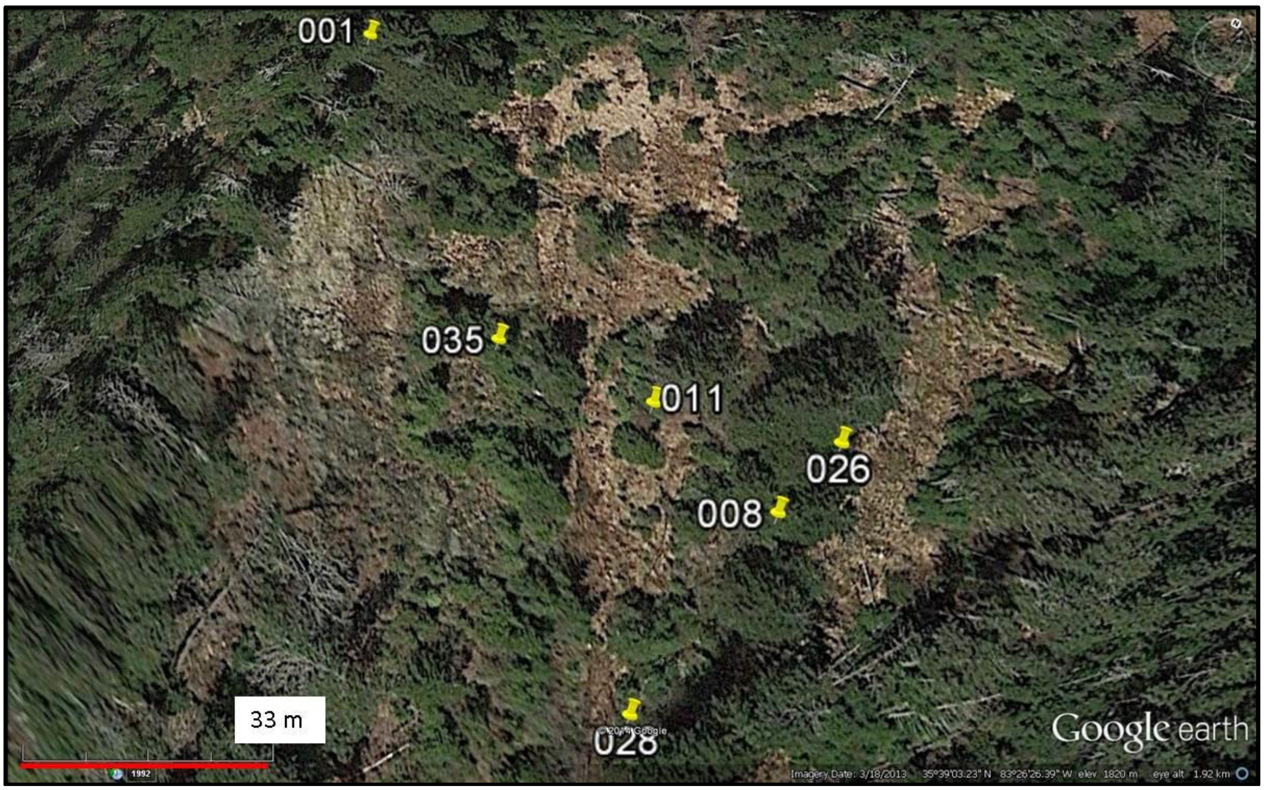


Figure 5.16: Google Earth map of the six trees affected by the 1909 event (no spatial pattern found).

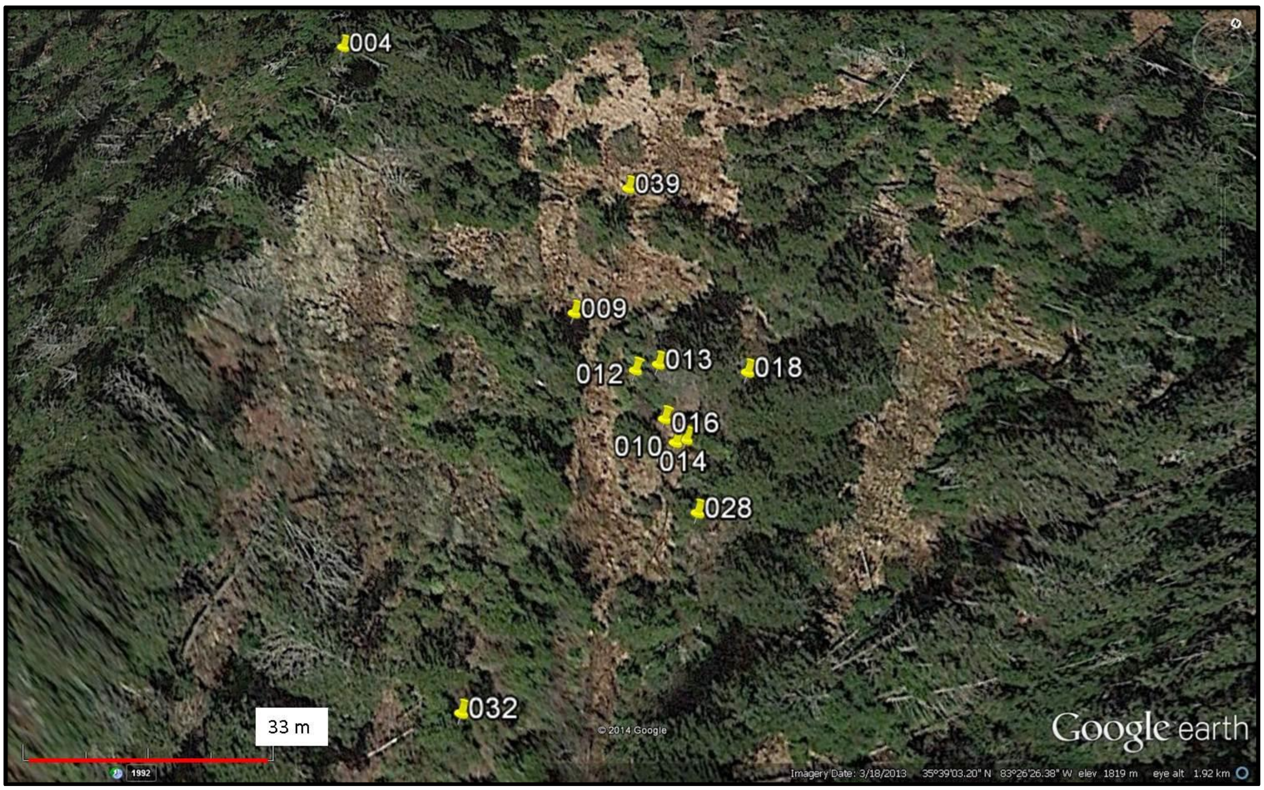


Figure 5.17: Google Earth map of the 11 trees affected by the 1981 event indicating a smaller event located along the central of the three slide sections studied.

Table 5.3: Possible debris slide dates from both visual and statistical analysis. Those confirmed by comparison with the control (LCR) are highlighted. The 1981 event was seen in the control comparison but not listed in visual and statistical results.

Combination of Possible Event Dates from Visual and Statistical Analyses				
Year	**Primary Response (S or R)**	**JOLTS Index or Visual**	**% Trees**	**Confirmed Event by Control?**
1825	S	JOLTS	14	NO
1836	S	JOLTS	27	NO
1858	S	JOLTS	11	NO
1893	S	Visual	12	NO
1909	S	JOLTS	13	YES
1918	S	JOLTS	25	NO
1922	S	Visual	21	NO
1940	R	Visual	15	NO
1944	R	Visual	15	NO
1952	S	Visual	38	YES
1952	S	JOLTS	21	YES
1953	S	Visual	21	YES
1959	R	JOLTS	12	NO
1960	R	Visual	15	NO
1968	S	Visual	15	NO
1975	R	Visual	12	NO
1975	R	JOLTS	12	NO
1986	R	JOLTS	15	NO
1992	R	JOLTS	21	NO
1996	S	Visual	12	NO
1997	S	Visual	32	NO
1998	S	Visual	26	NO
2005	R	Visual	12	NO
2005	R	JOLTS	38	NO

more localized data source on Mt. Le Conte would be more appropriate for assumptions on slide triggers, but data there are only available to the 1980s. The NOAA storm events database did not identify the 1951 cloudburst, a fact which indicated that the database may not work for localized studies such as this, performed on one mountain. Still, the 1909 and 1981 dates were not rejected as possible debris slide dates. The 1981 date, however, was more firmly supported by the identified spatial pattern.

In regression modelling, only four of 10 climate variables (Table 5.4) produced statistically significant models: current spring precipitation, previous summer precipitation, current July temperature, and previous fall PDSI (Table 5.5). Modelling tree growth based on current spring precipitation produced an r^2 value of 0.09; previous summer precipitation 0.04, current July temperature 0.04, and previous Fall PDSI 0.050, for a total of 0.22 or 22% of growth explained by these four climate variables. This percentage fell short of the 25–30% goal, and many of the dates identified by JOLTS persisted in the final residual chronology (Fig. 5.18). The progression of climate signal removal (Fig. 5.19) showed that extremes in the chronology were not significantly reduced despite the removal of four climate variables and the method could not be used to isolate the debris slide signal. Despite results from climate-growth analysis, inter-annual differences in climate parameters do not influence tree growth, or are not the limiting factors, in high elevation red spruce trees on Mt. Le Conte. The ultimate goal of regression modelling was to remove climate signal (noise) and isolate debris slide events (signal), a principle of aggregate tree growth. However, even after removing as much climate as possible, the debris slide signal could not be enhanced and the method did not prove useful

Table 5.4: Ten most significant ($p \leq 0.05$) climate variables (15-yr standardization) with correlations ≤ –0.20 or ≥ 0.20 from climate-growth analysis used in regression modelling.

Climate Variables Used to Model Tree Growth and Remove Climate Influence	
Climate Variable	**Correlation**
Previous August Precipitation	0.31
Current Spring Precipitation	–0.30
Previous Fall PDSI	0.25
Current July Temperature	0.24
Current March Temperature	–0.22
Current May Precipitation	–0.22
Previous Summer Precipitation	0.21
Current Summer Temperature	0.21
Previous August Temperature	–0.20
Current August Temperature	0.20

Table 5.5: Results from regression modelling of tree growth dependent on climate. Climate variables listed in all capital letters represent previous year, and those listed in lowercase represent current year P (total monthly precipitation), T (mean monthly temperature), and PDSI. Shaded models were found to be significant and totaled to represent 22% of growth explained by four climate variables.

Regression Modelling Results				
Climate Variable	**P value**	**r^2**	**Significant (yes/no)**	**% Explained**
AUG P	0.0791	0.027	NO	
Spring P	0.0011	0.088	YES	9%
FALL PDSI	0.0161	0.050	YES	5%
July T	0.0356	0.038	YES	4%
March T	0.0862	0.026	NO	
May P	0.7987	0.001	NO	
SUMMER P	0.0218	0.045	YES	4%
Summer T	0.2035	0.014	NO	
AUG T	0.4621	0.005	NO	
Aug T	0.2531	0.012	NO	
			TOTAL	22%

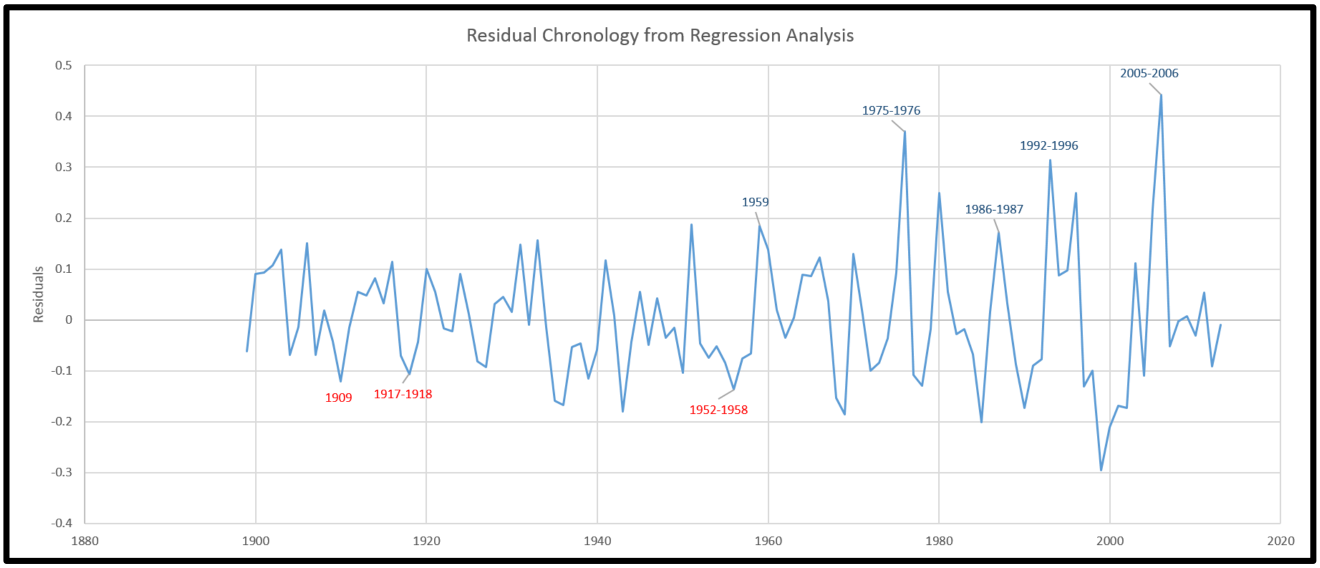


Figure 5.18: Final residual chronology produced through the removal of climate signals in regression modelling. Red represents suppression dates, and blue represents release dates. The goal of regression modelling was to remove climate influences. If successful, major suppression and release periods seen in the chronology would be reduced where caused by climate. However, this did not prove to be the case, as growth changes identified in the comparison with the control to have been caused by climate or other outside influences persisted despite the removal of four significant climate variables. This suggests that another control on growth, besides climate or debris slides, is more influential at LC01.

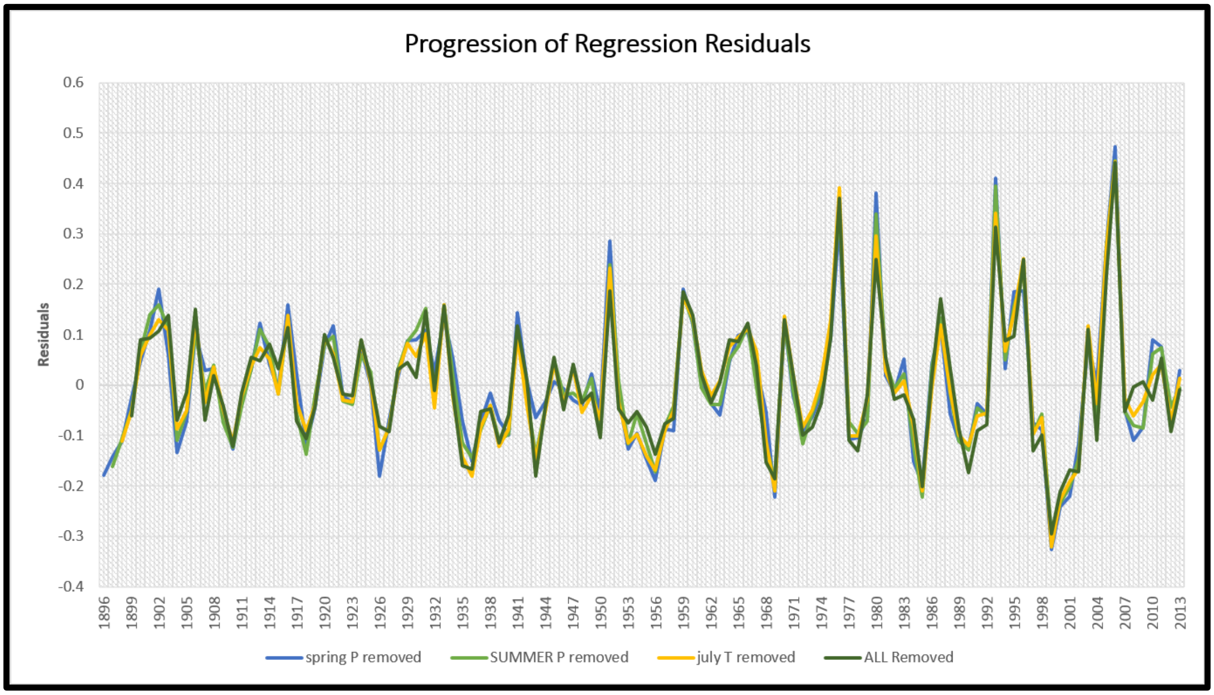


Figure 5.19: Progression of regression residual chronologies after each climate variable was removed. Removing these four climate variables changed little and did not help to isolate the debris slide signal.

in this study except to highlight the minimal influence of climate on the sampled trees. Climate is only one factor affecting growth in red spruce.

Possible debris slide event dates were also compared with the two climate variables with the strongest relationship found with growth at LC01 (spring precipitation and August precipitation) as well as with total yearly precipitation and average yearly temperature for eastern Tennessee (NCDC 2014). Due to the rejection of all possible dates except 1909, 1952, and 1981, only these three dates were checked in this final analysis. The comparison with spring precipitation data (Fig. 5.20) showed high values in 1909 which could have led to decreased growth in red spruce, according to a negative relationship (–0.30). However, high spring rainfall could have also caused a debris slide event at the site. Values for 1952 and 1981 were closer to the mean, but 1981 was bracketed by years with higher values of spring precipitation and followed by a period of decreased precipitation. The comparison with August precipitation (Fig. 5.21) showed more average values for all three years, but 1952 was followed by a dramatic and sustained decrease in August precipitation which would have added additional stress to trees at LC01 following the 1951 slide event. The relationship with previous August precipitation was found to be positive (0.31), meaning red spruce at LC01 prefer a wet previous August. Low values of August precipitation in the 1950s could have led to enhanced suppressions in stressed trees. The comparison with total yearly precipitation (Fig. 5.22) again showed a period of decreased precipitation after 1952, which would have added stress to trees affected by the 1951 slide event. The year 1981 was not a stressed year, but it was soon followed by a period of decreased precipitation in the later 1980s. This drought could have caused the 1981 suppression identified during the control vs. disturbed comparison. The comparison with

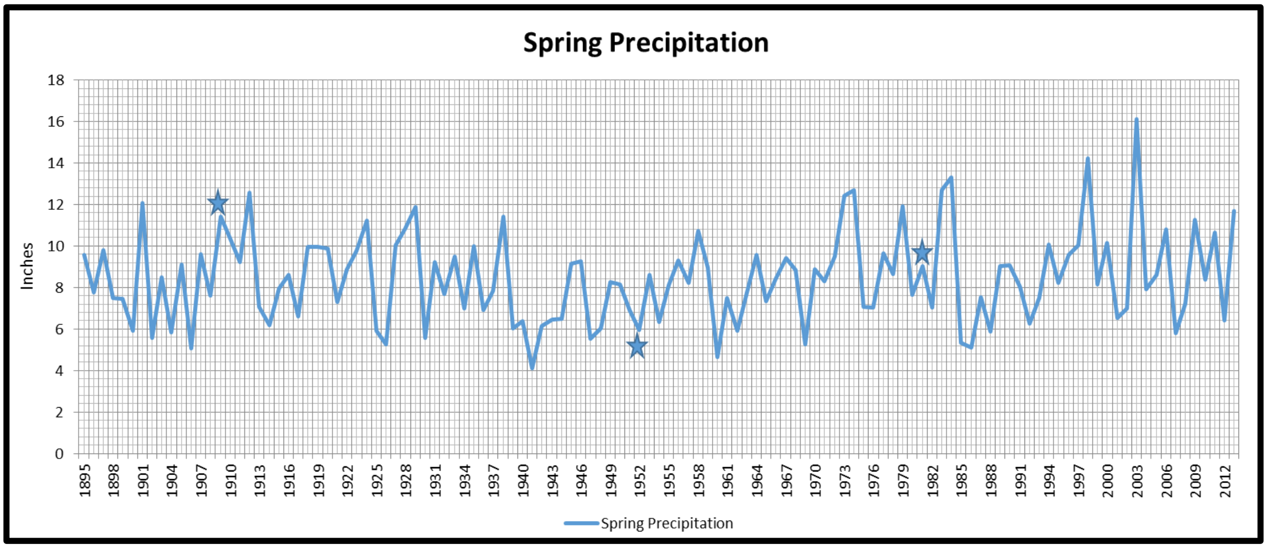


Figure 5.20: Graph of East Tennessee spring precipitation (April and May) for 1895-2013. Data from the NCDC. Stars indicate event years (suppression) compared with climate data. 1909 shows higher spring precipitation values which could have led to decreased growth according to a negative relationship (–0.30). Values for 1952 and 1981 were closer to the mean, but 1981 was bracketed by years with higher values of spring precipitation and followed by a period of decreased precipitation.

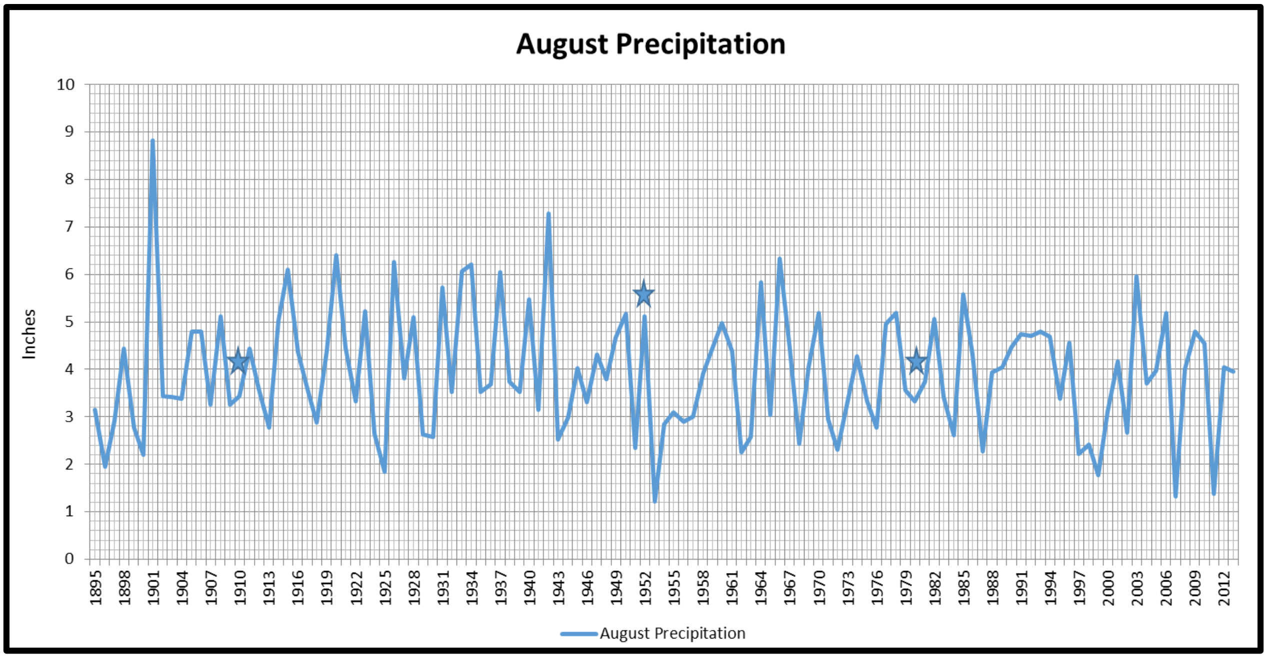


Figure 5.21: Graph of East Tennessee August precipitation for 1895–2013. Data from the NCDC. Stars indicate event years (suppression) compared with climate data. All three years show values closer to the mean, but 1952 is followed by a dramatic and sustained decrease in August precipitation which would have added additional stress to trees at LC01 already affected by the 1951 slide event. Relationship with previous August precipitation is positive (0.31) meaning red spruce at LC01 prefer a wet previous August.

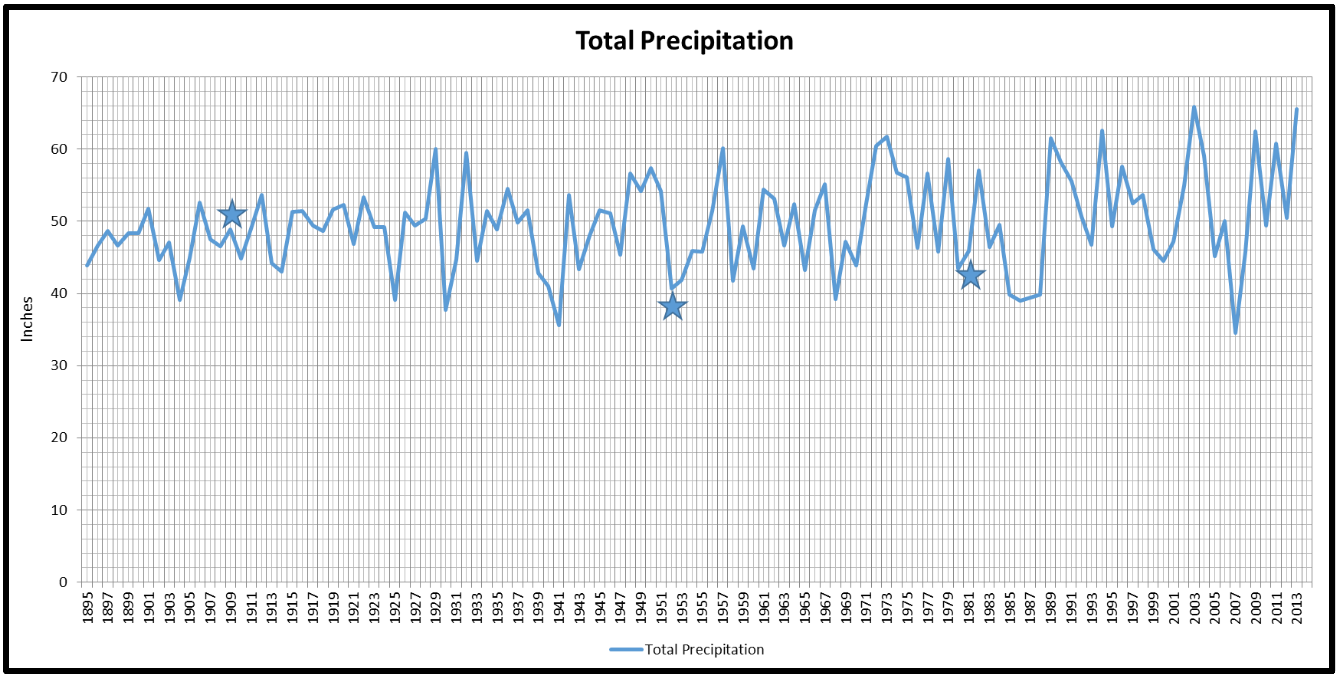


Figure 5.22: Graph of East Tennessee total yearly precipitation for 1895–2013. Data from the NCDC. Stars indicate event years (suppression) compared with climate data. 1952 marks the beginning of a period of decreased precipitation which would have added stress to trees affected by the 1951 slide event. 1981 does not seem to be a stressed year but it is soon followed by a period of decreased precipitation in the later 1980s.

average yearly temperature showed no extremes or relationships. Conclusions from this analysis however, are speculative due to the distance of the climate data source from the site and the principle of aggregate tree growth. Visually and statistically supported relationships between climate and tree growth only explain one piece of the puzzle. Further study is needed to more accurately determine the relationships between specific climate variables and possible debris slide events.

5.6.5 Debris Slide History

Combined visual and statistical analysis of suppression and release sequences in trees at LC01 provided a list of 20 possible debris slide dates (Table 5.3), but after the removal of climate influence on disturbance signals, only three dates remained: 1909, 1952, and 1981. The 1981 event was noted during the comparison of the control and disturbed chronology but was not identified by either the visual or statistical identification of possible event dates, except when identified as a cluster of dates from 1981–1984. In addition, both the 1909 and 1981 events were found to be possibly associated with climate influences. Even though this part of the analysis was speculative, climate could not be ruled out for these two dates. Tree growth, however, is not explained by one single climate variable, so the suppressions of 1909 and 1981 were maintained according to findings in the comparison with the control chronology. Even though climate could not be ruled out, enhanced suppressions in growth in 1981, and suppressions in growth in 1909, despite increases seen in LCR, indicated that something else affected growth. A debris slide event, even a small rock fall or debris slide reactivation, could not be ruled out for 1909 or 1981, and the spatial pattern of recording trees for 1981 supported this theory. The possible combination of both climate and disturbance-controlled suppression is supported by the 1952 event, which showed suppression in both the control and disturbed chronology. Decreased growth, however, was more dramatic and sustained in LC01. August precipitation and total yearly precipitation data for east Tennessee showed decreases in the 1950s, which could have led to an enhancement of suppression at LC01. However, a triggering event in 1951 was known (Bogucki 1970, 1976), which allowed us to conclude that a debris slide occurred at LC01 in 1951 followed by a growth suppression in 1952.

5.7 Discussion

Although initial visual and statistical dendrogeomorphic analysis revealed 20 possible debris slide dates at LC01, only three were retained as possible event dates at the site following the removal of climate and other influences through a difference chronology, comparisons with a control, regression modelling, and comparisons with climate data. Suppressions in growth beginning in 1909 and 1981 were not supported by archival records or by all analyses but were clearly defined in comparisons with a control chronology. In addition, the 1981 event was supported by a spatial pattern (affected trees concentrated in the central of the three studied slide areas). The only debris slide event date that could be confidently confirmed by this study however, was the one in 1952, the date when growth suppression would have begun following the known cloudburst event late in the growing season, September 1951 (Bogucki 1970, 1976). However, this finding is in itself important as it serves as a confirmation of dendrogeomorphic methods at the study site, Mt. Le Conte, and perhaps even GSMNP as a whole. This thesis is the first known study of its kind performed in GSMNP and especially on Mt. Le Conte. Finding the 1952 suppression served as a calibration of the methods and helped provide methodological support for the 1951 debris slide event date, showing how dendrogeomorphic findings can help support, validate, or correct archival data.

The initial finding of 20 possible debris slide dates, and further rejection of all but three also highlights the importance of first determining and then removing as many climate signals as possible from a chronology intended for dendrogeomorphic analysis. Climate-growth analysis revealed a small yet significant climate influence at LC01, and even though attempts to remove this influence directly through regression modelling proved unhelpful, the matching growth patterns seen in comparisons with a control revealed an unknown external factor, such as some climate or other variable, that affected both LCR and LC01 trees. If dates identified in the initial visual and statistical analyses of suppression and release sequences would have been maintained without the important step of climate removal and control comparisons, these dates would have been grossly inaccurate. Climate-growth analysis should always be an initial step in dendrogeomorphic studies.

Results also revealed the complicated nature of isolating climate and geomorphological disturbances from each other. The 1951 event at LC01 was known to correspond with a documented cloudburst event, but also corresponded with decreased total yearly precipitation and August precipitation in the 1950s. In this case, the decrease in moisture added stress to trees affected by the debris slide and enhanced suppression. Comparing LCR and LC01 helped to identify enhanced suppression at LC01 and a likely debris slide event. Findings such as this follow the theory of aggregate tree growth, where tree age, climate, internal, and external factors all influence tree growth. The 1952–1958 growth suppression was not only a function of the debris slide and decreased precipitation, but also of many other factors currently unknown. The combination of many methods (the ensemble method) helped us to make sure that the 1952 event was not interpreted as a drought only and that we did not disregard it as a debris slide date.

CHAPTER SIX

SUMMARY AND IMPLICATIONS

6.1 Major Conclusions and Implications

6.1.1 Chapter Three: Feasibility of Dendrogeomorphic Study in the Southeast: A Case Study on Mt. Le Conte, Great Smoky Mountains National Park, Tennessee, U.S.A.

Despite the rarity of dendrogeomorphic studies performed in GSMNP and the Appalachian Mountains of eastern North America, trees have the potential to record evidence of debris slides in the tree-ring record. During exploration of three debris slide scars on Mt. Le Conte in GSMNP, multiple “events” (Shroder 1978) were identified that affected trees and will, or have already been, recorded by the trees for future study. We found all the forms of evidence outlined by Shroder (1978) on Mt. Le Conte in GSMNP. The identification of apparent debris slide influence on trees and external “events” known to induce internal “responses” (Shroder 1978) in trees makes the application of dendrogeomorphic methods valid in GSMNP. The likelihood is also high that dendrogeomorphology is a feasible approach to answering geomorphic questions in the southeastern U.S. The capacity for tree-ring reconstruction of past debris slide events exists in GSMNP and opens doors for future work in the park and perhaps elsewhere in the Appalachian Mountains and the southeastern U.S.

6.1.2 Chapter Four: Analyzing the Impact of Debris Slide Disturbance on the Temporal Stability of Climate-Growth Relationships in Red Spruce, Mt. Le Conte, GSMNP, Tennessee

Despite living in a known area of disturbance, red spruce at LC01 showed multiple significant ($p \leq 0.05$) growth relationships with climate variables over the period 1896–2013. A few of these relationships were also temporally stable. The strongest relationship was with previous August precipitation ($r = 0.31$), but the strongest seasonal relationship was with current spring precipitation ($r = -0.30$). A negative, but not significant at $p \leq 0.05$, relationship with current April precipitation was temporally stable over the longest period with only one weakened period in the late 2000s. The general pattern favorable to red spruce growth, revealed in climate-growth relationships of the final 15-year detrended chronology, was a dry and cool current spring followed by a warm and dry current summer. However, red spruce also favored a wet previous summer, according to both the strong positive previous August relationship and the relationships with positive fall and summer previous year PDSI values.

In contrast to the findings from previous studies (Biermann 2009; White 2010; Li 2011), we did not discover any major shifts from one climate-growth relationship to another (temperature to precipitation or vice versa) during the mid-20th century. However, a few notable changes in climate-growth relationships occurred around this time. The relationship with current January temperature weakened and was no longer stable after the 1960s, and a weak relationship with current March temperature emerged after the 1960s. The relationship with previous August precipitation became more dominant after the 1950s, but the relationship with previous May precipitation became less pronounced after the 1960s. A weak relationship with current May precipitation also emerged after the 1950s. For PDSI, the weak and less stable previous October PDSI relationship emerged and seemed to strengthen slightly after the 1950s. No shifts from precipitation to temperature relationships, as seen in the reviewed literature, were noted. The strongest and most temporally stable relationships, according to forward evolutionary analysis, were negative with current April precipitation and positive with current July temperature, and these relationships remained the most constant and temporally stable through the studied period. The existence of a significant climate signal means that isolating geomorphic disturbances from those caused by climate will be more difficult at the site and perhaps in GSMNP and southeastern U.S.

6.1.3 Chapter Five: Dendrogeomorphic Analysis of Debris Slides on Mt. Le Conte, GSMNP, Tennessee, U.S.A.

Even though initial visual and statistical dendrogeomorphic analysis revealed 20 possible debris slide dates at LC01, only three were retained as possible event dates at the site (1909, 1951, 1981) after the removal of climate and other influences through a difference chronology, comparisons with a control, regression modelling, and comparisons with climate data. Suppressions in growth beginning in 1909 and 1981 were not supported by archival records or by all analyses but were clearly defined in comparisons with a control chronology. In addition, the 1981 event was supported by a spatial pattern (affected trees concentrated in the central of the three studied slide areas). The only debris slide event date that could be confidently confirmed by this study however, occurred in 1952, the date when growth suppression would have begun following the known cloudburst event late in the growing season, September 1951 (Bogucki 1970, 1976). However, this finding is in itself important as it serves as a confirmation of dendrogeomorphic methods at the study site, Mt. Le Conte, and perhaps even GSMNP as a whole. This thesis is the first known study of its kind performed in GSMNP. Finding the 1952 suppression served as a calibration of the methods and helped provide methodological support for the 1951debris slide event date, showing how dendrogeomorphic findings can help support, validate, or correct archival data.

The initial finding of 20 possible debris slide dates and further rejection of all but three highlighted the importance of first determining and then removing as many climate signals as possible from a chronology intended for dendrogeomorphic analysis. Climate-growth analysis revealed a small yet significant climate influence at LC01, and even though attempts to remove this influence directly through regression modelling proved unhelpful, the matching growth patterns seen in comparisons with a control revealed an unknown external factor, such as some climate or other variable, that affected trees at both LCR and LC01. If dates identified in the initial visual and statistical analyses of suppression and release sequences would have been retained without the important step of climate removal and control comparisons, these dates would have been grossly inaccurate. Climate-growth analysis should always be an initial step in dendrogeomorphic studies.

Results also revealed the complicated nature of isolating climate and geomorphological disturbances from each other. The 1951 event at LC01 was known to correspond with a documented cloudburst event, but also corresponded with decreased total yearly precipitation and August precipitation in the 1950s. In this case, the decrease in moisture added stress to trees affected by the debris slide and enhanced suppression. Comparing growth patterns at LCR and LC01 helped to identify enhanced suppression at LC01 and a likely debris slide event. Findings such as this follow the theory of aggregate tree growth, where tree age, climate, internal, and external factors all influence tree growth. The 1952–1958 growth suppression was not only a function of the debris slide and decreased precipitation, but also of many other factors yet unknown. The combination of many methods (the ensemble method) helped ensure that the 1952 event was not interpreted as a drought only and that we did not disregard it as a debris slide date.

6.2 Summary of Research Questions and Answers

6.2.1 Chapter Three: Can we find evidence in the field that trees in the southeast, and especially GSMNP, will record evidence of debris slide events?

Trees on Mt. Le Conte, and likely GSMNP and the southeastern U.S., have recorded and will record evidence of debris slide events. During exploration of three debris slide scars on Mt. Le Conte in GSMNP, we found all the forms of evidence outlined by Shroder (1978). The identification of external "events" known to cause internal "responses" (Shroder 1978) in trees validates the use of dendrogeomorphic methods in GSMNP and likely makes the use of dendrogeomorphic methods in the southeastern U.S. feasible for the reconstruction of debris slide histories.

6.2.2 Chapter Four: Do significant climate-growth relationships exist between red spruce and monthly climate variables in a disturbed environment?

The strongest relationship identified in climate-growth analysis of LC01 red spruce was with previous August precipitation ($r = 0.31$, $p \leq 0.05$) (Fig. 4.4). Significant relationships were also found with current March temperature ($r = -0.22$, $p \leq 0.05$), current May precipitation ($r = -0.22$, $p \leq 0.05$), current July temperatures ($r = 0.24$, $p \leq 0.05$), and previous August, September, and October PDSI ($r = 0.26$, 0.22, 0.25, $p \leq 0.05$ respectively). Four significant ($p \leq 0.05$) seasonal relationships were found: previous summer precipitation ($r = 0.21$), previous fall PDSI ($r = 0.25$), current summer temperatures (r = 0.21), and current spring precipitation (r = –0.30). The existence of significant climate influences on red spruce growth at LC01 prompted the attempted removal of this influence to better isolate the debris slide signal.

6.2.3 Chapter Four: Which detrending method works best for isolating the strongest climate signals in the specific disturbed environment?

The 15-year spline resulted in a standard chronology that had the strongest climate signal, based on results from tests of six detrending methods (linear, exponential, 15, 20, 25, and 32-year splines). Spline tests were evaluated based on which detrending method resulted in more consistently stronger relationships with climate variables. The 15-year spline curve was chosen to develop the final standard chronology used for climate-growth analysis in chapter 4.

6.2.4 Chapter Four: Are these relationships temporally stable or do major shifts dominate the climate signal?

No climate-growth relationship was temporally stable over the entirety of the tested period, but the relationship with current July temperatures was temporally stable through all of the 117-year period except when the years 1976–1983 were added, which resulted in correlations below 0.20. A relationship with current January temperature remained stable up to the 1970s, and a weaker relationship with current March temperatures emerged after the 1960s. Relationships with precipitation revealed a higher level of temporal stability, especially with current April precipitation, which remained strong and stable until near the end of the tested period or until the late 2000s. A relationship with current May precipitation was stable but weaker beginning around 1950. The strongest climate variable relationship revealed through correlation analysis, previous August precipitation, was stable after 1950, with pockets of strong correlation periods in earlier years. A positive relationship with previous May precipitation weakened in the 1970s. A weak but stable relationship with previous October PDSI emerged in the 1950s. However, PDSI variables showed major shifts in overall correlation values through time, indicating that some events caused major shifts in the growth relationships of red spruce with monthly PDSI in the 1940s, 1950s, and 1974.

6.2.5 Chapter Five: What are the date(s) of slide activations or reactivations at the debris slide site LC01?

Possible dates identified for slide activation/reactivation were 1909, 1952, and 1981. The year 1909 was supported by JOLTS analysis and the comparison of the control and disturbed chronologies. The year 1981 was not identified in either visual or JOLTS analysis until the period was extended to include 1982–1984. This allowed the inclusion of 11 trees recording (combination of visual and JOLTS results) the 1981 event. In addition, these trees, when mapped, revealed a spatial clustering on the central of the three slide areas studied at LC01, indicating a smaller event may have occurred on that portion of the original slide scar.
The only confidently confirmed debris slide date was 1951. This date marks the 1951 September cloudburst event, which would have left evidence in the following growing season, 1952. Because this date corresponds with a known event, it can be confirmed as a debris slide. However, the dates 1909 and 1981 cannot be discarded. Further research is needed to better support these dates.

6.2.6 Chapter Five: What are the possible triggers of these debris slides?

The 1952 suppression event was the only debris slide with a definite trigger, the 1951 cloudburst. Triggers for the other events could not be identified, but one thunderstorm known to have caused wind and rain damage was listed in the NCDC Storm Event database in September 1980. More localized climate data are needed. We observed possible climate causes of the 1909 and 1981 suppressions in the comparison of event dates with eastern Tennessee climate data. High spring precipitation was observed in 1909 which could have reduced growth (based on a negative relationship between spring precipitation and red spruce growth), but may also have triggered an event. The year 1981 was bracketed by years with higher values of spring precipitation and followed by a period of decreased spring precipitation. The year 1981 was also followed by a period of decreased total yearly precipitation. This drought could have caused the 1981 suppression. These climate influences however, cannot be assumed to have caused the suppressions entirely, based on the large spatial scale of the climate data and the principle of aggregate tree growth.

6.2.7 Chapter Five: Which forms of tree-ring evidence worked best to identify debris slide dates in GSMNP?

We used suppression and release sequences in red spruce growth as the primary evidence of debris slide events in this study. Because of the potential impact of slope creep on tree growth and inability to reach the debris slide bases safely or efficiently, tilting was disregarded as evidence of debris slides at LC01. Scarring was considered supportive evidence only due to the low chance of finding a scar with increment cores and the inability to collect wedges or cross sections. Only one scar was identified but dated to the 1990s and did not support any possible debris slide dates. Succession was not applicable as Fraser fir were first to reestablish on the slide scar and sampling of this species was prohibited by the park.

6.3 Future Research

The following research topics were developed based on results from this study. Further research is needed in these areas.

- Quantification and possible relationship between climate and debris slide events
    - Possible climate causes of suppressions in 1909 and 1981 were identified but these climate suppressions could not rule out debris slides (the 1952 suppression caused by a debris slide was intensified by a drought). In addition, some of these climate variables, such as increased spring precipitation, could have also been triggers of debris slides. Periods of increased rainfall can lead to optimal conditions for a debris slide to occur, given that enough material has collected on the slope, following a previous event, to slide downslope. Can highs and lows in significant precipitation variables be supported as evidence of specific triggers of debris slide events?
- Possible shifts in climate response due to disturbance at study site
    - In chapter four, shifts in climate relationships were found to correspond with possible disturbance dates (1975 was later ruled out), but correlation does not indicate causation. Can disturbance patterns at a site change climate-growth

relationships or cause relationships to appear or disappear? Is a debris slide a significant enough event to completely overshadow climate signals?

- Further investigation of the 1909 and 1981 event dates
    - The years 1909 and 1981 were supported as possible debris slide dates based mainly on their identification in the comparison of the LCR control and disturbed LC01 chronologies, but they could not be as firmly supported as the 1952 event date. More work is needed to determine if these dates truly represent debris slides.

REFERENCES

Alestalo, J. (1971). Dendrochronologic interpretation of geomorphic processes. *Fennia*, *105*, 4–140.

Anchukaitis, K. J., R. D. D'Arrigo, L. Andreu-Hayles, D. Frank, A. Verstege, A. Curtis, B. M. Buckley, G. C. Jacoby, and E. R. Cook. (2013). Tree-ring reconstructed summer temperatures from northwestern North America during the last nine centuries. *Journal of Climate*, *26*, 3001–3012.

Arbellay, E., M. Stoffel, and M. Bollschweiler. (2010). Dendrogeomorphic reconstruction of past debris-flow activity using injured broad-leaved trees. *Earth Surface Processes and Landforms*, *35*(4), 399–406.

Biermann, C. P. (2009). Twentieth Century Changes in the Climate Response of Yellow Pines in Great Smoky Mountains National Park, Tennessee, U.S.A. Master's Thesis, The University of Tennessee, Knoxville.

Biondi, F. and K. Waikul. (2004). DENDROCLIM2002: a C++ program for statistical calibration of climate signals in tree-ring chronologies. *Computers and Geosciences*, *30*, 303–311.

Bogucki, D. J. (1970). Debris Slides and Related Flood Damage Associated with the September 1, 1951 Cloudburst in the Mt. Leconte-Sugarland Mountain Area, Great Smoky Mountains National Park. PhD Dissertation, The University of Tennessee, Knoxville.

Bogucki, D. J. (1976). Debris slides in the Mt. Le Conte area, Great Smoky Mountains National Park, U.S.A. *Geografiska Annaler: Physical Geography*, *58*(3), 179–191.

Bollschweiler, M. and M. Stoffel. (2010). Changes and trends in debris-flow frequency since AD 1850: Results from the Swiss Alps. *The Holocene, 20*(6), 907–916.

Braam, R. R., E. E. J. Weiss, and P. A. Burrough. (1987). Spatial and temporal analysis of mass movement using dendrochronology. *Catena, 14*(6), 573–584.

Braun, E. L. (1950). *Deciduous Forests of Eastern North America*. New York: Hafner Publishers.

Briffa, K., F. H. Schweingruber, P. D. Jones, T. J. Osborn, S. G. Shiyatov, and E. A. Vaganov. (1998). Reduced sensitivity of recent tree-growth to temperature at high northern latitudes. *Nature*, *391*, 678–682.

Briffa, K. (2000). Annual climate variability in the Holocene: interpreting the message from ancient trees. *Quaternary Science Review*, *19*, 87–105.

Brose, P. H. and T. A. Waldrop. (2010). A dendrochronological analysis of a disturbance-succession model for oak-pine forests of the Appalachian Mountains, USA. *Canadian Journal of Forest Research*, *40*, 1373–1385.

Busing, R. T. and E. F. Pauley. (1994). Mortality trends in a southern Appalachian red spruce population. *Forest Ecology Management*, *64*, 41–45.

Butler, D. R. and G. P. Malanson. (1985). A history of high-magnitude snow avalanches, southern Glacier National Park, Montana, U.S.A. *Mountain Research and Development*, *5*(2), 175–182.

Butler, D. R., G. P. Malanson, and J. G. Oelfke. (1987). Tree-ring analysis and natural hazard chronologies: minimum sample sizes and index values. *The Professional Geographer, 39*(1), 41–47.

Carrara, P. E., and J. M. O'Neill. (2003). Tree-ring dated landslide movements and their relationship to seismic events in southwestern Montana, USA. *Quaternary Research*, *59*(1), 25–35.

Coile, T. S. (1936). The effect of rainfall and temperature on the annual radial growth of pine in the southern United States. *Ecological Monographs*, 6(4), 535–562.

Clague, J. J. (2010). Dating landslides with trees. *Trees Rings and Natural Hazards: A State-of-the-Art*. M. Stoffel, M. Bollschweiler, D. Butler, & B. Luckman (eds.). New York: Springer, 81–90.

Clark, G. M. (1987). Debris slide and debris flow historical events in the Appalachians south of the glacial border. *Reviews in Engineering Geology, 7*, 125–138.

Clark, G. M., P. T. Ryan Jr., and E. C. Drumm. (1987). Debris slides and debris flows on Anakeesta Ridge, Great Smoky Mountains National Park, Tennessee. *Landslides of Eastern North America*, USGS Circular, p. 18–19.

Cook, E. R. ITRDB NC002. PCRU Clingman's Dome Chronology. http://hurricane.ncdc.noaa.gov/pls/paleox/f?p=519:1::::P1_STUDY_ID:2964. Accessed 01/06/2014

Cook, E. R. (1985). *A Time Series Analysis Approach to Tree-Ring Standardization*. Dissertation, University of Arizona.

Cook, E. R. and A. H. Johnson. (1989). Climate change and forest decline: a review of the red spruce case. *Water, Air, and Soil Pollution*, *48*, 127–140.

Cook, E. R., A. H. Johnson, and T. J. Blasing. (1987). Forest decline: modeling the effect of climate in tree rings. *Tree Physiology*, *3*, 27–40.

Cook, E. R., D.M. Meko, D.W. Stahle, and M.K. Cleaveland. (1999). Drought reconstructions for the continental United States. *Journal of Climate*, 12(4), 1145–1162.

Cook, E. R., M.A. Kablack, and G.C. Jacoby. (1988). The 1986 drought in the southeastern United States: how rare an event was it? *Journal of Geophysical Research*, 93(D11), 14257–14260.

Crozier, M. J. (1984). Field Assessment of Slope Instability, in *Slope Instability*, Brunsden, D., and Prior, D. (eds.), John Wiley and Sons, 103–142.

Cseke, J. J. (2003). A Dendrochronological Approach for Dating Individual Small-Scale Canopy Disturbance Events, Great Smoky Mountains National Park, Tennessee, USA. Masters Thesis, The University of Tennessee, Knoxville.

D'Arrigo, R. D., R. K. Kaufmann, N. Davi, G. C. Jacoby, C. Laskowski, R. B. Myeni, and P. Cherubini. (2004). Thresholds for warming-induced growth decline at elevational treeline in the Yukon territory. *Global Biogeochemistry Cycles*, *18* (3), DOI: 10.1029/2004GB002249.

D'Arrigo, R. D., R. Wilson, B. Liepert, and P. Cherubini. (2008). On the divergence problem in northern forests: a review of the tree-ring evidence and possible causes. *Global and Planetary Change*, *60*, 289–305.

D'Arrigo, R. D., R. Wilson, and K. J. Anchukaitis. (2013). Volcanic cooling signal in tree ring temperature records for the past millennium. *Journal of Geophysical Research: Atmospheres*, *118*, 9000–9010.

DeWeese, G. G., H. D. Grissino-Mayer, C. W. Lafon, and S. R. Aldrich. (2010). Evaluating the dendroclimatological potential of central Appalachian Table Mountain pine (Pinus pungens Lamb.). *Dendrochronologia*, 28(3), 173–186.

Easterbrook, D. J. (1999). *Surface Processes and Landforms*. Prentice-Hall:New Jersey.

Eschner, A. R., and J. H. Patric. (1982). Debris avalanches in eastern upland forests. *Journal of Forestry, 80*(6), 343–347.
Fantucci, R., and M. Sorriso-Valvo. (1999). Dendrogeomorphological analysis of a slope near Lago, Calabria (Italy). *Geomorphology, 30*(1-2), 165–174.
Feldkamp, S. M. (1984). Revegetation of Upper Elevation Debris Slide Scars on Mount Le Conte in the Great Smoky Mountains National Park. Masters Thesis, The University of Tennessee, Knoxville.
Finch, R. H. (1937). A tree-ring calendar for dating volcanic events at Cinder Cone, Lassen National Park, California. *American Journal of Science*, *33*, 140–146.
Flaccus, E. (1959). Revegetation of landslides in the White Mountains of New Hampshire. *Ecology, 40*(4), 692–703.
Fritts, H. C. (1976). *Tree Rings and Climate*. Academic Press, New York, 567 pp.
Grissino-Mayer, H. D. 1995. Tree-Ring Reconstructions of Climate and Fire History at El Malpais National Monument, New Mexico. PhD dissertation, The University of Arizona, Tucson.
Grissino-Mayer, H. D. (2001). Evaluating crossdating accuracy: A manual and tutorial for the computer program COFECHA. *Tree-Ring Research, 57*, 205–221.
Grissino-Mayer, H. D. and D. R. Butler. (1993). Effects of climate on growth of shortleaf pine (*Pinus echinata* Mill.) in northern Georgia: a dendroclimatic study. *Southeastern Geographer*, 33(1), 65–81.
Grissino-Mayer, H. D. and H. C. Fritts. (1995). Dendroclimatology and dendroecology in the Pinaleño Mountains. Pages 100-120 in C.A. Istock and R.S. Hoffman, eds., *Storm over a Mountain Island: Conservation Biology and the Mt. Graham Affair*. University of Arizona Press: Tucson, Arizona.
Grissino-Mayer, H.D., M.S. Rosenberger, and D.R. Butler. (1989). Climatic response in tree rings of loblolly pine from north Georgia. *Physical Geography*, 10(1), 32–43.
Hack, J.T. and J.C. Goodlett (1960). Geomorphology and forest ecology of a mountain region in the Central Appalachians. USGS *Professional Paper* 347.
Hadley, J. B. and R. Goldsmith. (1963). Geology of the Great Smoky Mountains, Tennessee and North Carolina. USGS *Professional Paper* 349-B.
Hansen, J., I. Fung, A. Lacis, S. Lebedeff, D. Rind, R. Ruedy, G. Russell, and P. Stone. (1988). Global climate changes as forecast by the GISS 3-D model. *Journal of Geophysical Research*, *93*, 9341–9364.
Henderson, J. P. (1997). Debris Slide Susceptibility Analysis in the Mt. LeConte-Newfound Gap Area of the Great Smoky Mountains, Tennessee and North Carolina. Masters Thesis, The University of Tennessee, Knoxville.
Holmes, R. L. (1983). Computer assisted quality control in tree-ring dating and measurement. *Tree-Ring Bulletin*, *43*, 69–78.
Holmes, R. L. (1999). JOLTS. Dendrochronology program library and the dendroecology program library. Laboratory of Tree-Ring Research, University of Arizona, Tucson, Arizona, www.ltrr.arizona.edu/pub/dpl-mac/68k/dpl.txt Accessed 12/9/13.
Hull, J. C., and R. C. Scott. (1982). Plant succession on debris avalanches of Nelson County, Virginia. *Castanea, 47*(2), 158–176.

Hupp, C. R., W. R. Osterkamp, and J. L. Thornton. (1987). Dendrogeomorphic evidence and dating of recent debris flows on Mount Shasta, Northern California. USGS *Professional Paper* 1396-B.

Hupp, C. R. (1983). Geo-botanical evidence of late Quaternary mass wasting in block field areas of Virginia. *Earth Surface Processes and Landforms, 8*(5), 439–450.

Innes, J. L. (1991). High-altitude and high-latitude tree growth in relation to past, present, and future global climate change. *The Holocene*, *1*, 168–173.

International Tree-Ring Data Bank (ITRDB). (2014a). *User Guide to COFECHA Output Files*. http://www.ncdc.noaa.gov/paleo/treering/cofecha/userguide.html. Accessed 4/16/2014.

International Tree-Ring Data Bank (ITRDB). (2014b). *Median COFECHA Chronology Statistics by Species*. http://www.ncdc.gov/paleo/treering/cofecha/speciesdata.html. Accessed 4/16/2014.

Jacoby, G. C. and R. D. D'Arrigo. (1989). Reconstructed northern hemisphere annual temperature since 1671 based on high-latitude tree-ring data from North America. *Climatic Change*, *14*, 39–59.

Jacoby, G. C. and R. D. D’Arrigo. (1995). Tree-ring width and density evidence of climatic potential forest change in Alaska. *Global Biogeochemistry Cycles*, *9*(2), 227–234.

Johnson, A. H., E. R. Cook, and T. G. Siccama. (1988). Climate and red spruce growth and decline in the northern Appalachians. *Proceedings of the National Academy of Sciences*, *85*, 5369–5373.

Johnson, A. H., E. R. Cook, T. G. Siccama, J. J. Battles, S. B. McLaughlin, and D. C. LeBlanc. (1995). Comment: synchronic large-scale disturbances and red spruce decline. *Canadian Journal of Forest Research*, *25*, 851–858.

Kauppi, P. and M. Posch. (1985): Sensitivity of boreal forests to possible climatic warming. *Climatic Change*, *7*, 45–50.

Keefer D. (1984). Landslides caused by earthquakes. *Geological Society of America Bulletin*, *95*(4), 406–421.

LaMarche, V. C. (1966). An 800-year history of stream erosion as indicated by botanical evidence. USGS *Professional Paper* 550, 83–86.

LaMarche, V. C. (1968). Rates of slope degradation as determined from botanical evidence, White Mountains, California. USGS *Professional Paper* 352-I, 341–377.

Larsen, J. A. (1989). *The Northern Forest Border in Canada and Alaska. Biotic communities and ecological relationships*. Ecological Studies 70. New York: Springer Verlag.

Lawrence, D. B. (1946). The technique of dating recent prehistoric glacial fluctuations from tree data. *Mazama*, *28*(13), 57–59.

Lawrence, D. B. (1950). Estimating dates of recent glacier advances and recession rates by studying tree growth layers. *Transactions, American Geophysical Union*, *31*(2), 243–248.

LeBlanc, D. C., N. S. Nicholas, and S. M. Zedaker. (1992). Prevalence of individual-tree growth decline in red spruce populations of the southern Appalachian Mountains. *Canadian Journal of Forest Research*, *22*, 905–914.

Li, Y. (2011). Dendroclimatic Analysis of Climate Oscillations for the Southeastern United States from Tree-Ring Network Data. Master’s Thesis, The University of Tennessee, Knoxville.

Matmon, A., P. R. Bierman, J. Larsen, S. Southworth, M. J. Pavich, R. Finkel, and M. W. Caffee. (2003). Erosion of an ancient mountain range, the Great Smoky Mountains, North Carolina and Tennessee. *American Journal of Science, 303*(9), 817–855.

McGee, W. J. (1892). A fossil earthquake. *Geological Society of America Bulletin, 4*, 411–414.

McLaughlin, S. B., D. J. Downing, T. J. Blasing, E. R. Cook, and H. S. Adams. (1987). An analysis of climate and competition as contributors to decline of red spruce in high elevation Appalachian forests of the Eastern United States. *Oecologia, 72*, 487–501.

Moore, H. L. (1988). *A Roadside Guide to the Geology of the Great Smoky Mountains National Park*. Knoxville, Tennessee: University of Tennessee Press. 25–34.

NCDC. (2014). National Climatic Data Center. Department of Commerce, National Oceanic and Atmospheric Administration, Asheville, NC, http://www.ncdc.noaa.gov. Accessed 3/20/2014.

NCDC Storm Events Database. (2014). National Climatic Data Center. Department of Commerce, National Oceanic and Atmospheric Administration, Asheville, NC. http://www.ncdc.noaa.gov/stormevents/ Accessed 8/4/2014.

Orvis, K. H. and H. D. Grissino-Mayer. (2002). Standardizing the reporting of abrasive papers used to surface tree-ring samples. *Tree-Ring Research*, *58*, 47–50.

Pauley, E. F. (1993). The Influence of Episodic Reproduction by Red Spruce on Long-Term Forest Dynamics in the Cranberry Wilderness, West Virginia. PhD Dissertation, The University of Tennessee, Knoxville.

Ryan, P. T., Jr. (1989). Debris Slides and Flows on Anakeesta Ridge Within the Great Smoky Mountains National Park Tennessee, U.S.A. Masters Thesis, The University of Tennessee, Knoxville.

Saez, J., C. Corona, M. Stoffel, L. Astrade, F. Berger, and J. Malet. (2012). Dendrogeomorphic reconstruction of past landslide reactivation with seasonal precision: The Bois Noir landslide, southeast French Alps. *Landslides, 9*(2), 189–203.

Schneider, R.H. (1973). Debris Slides and Related Flood Damage Resulting from Hurricane Camille, 19-20 August, and Subsequent Storm, 5-6 September 1969 in the Spring Creek Drainage Basin, Green-Brier County, West Virginia. PhD Dissertation, The University of Tennessee, Knoxville.

Schweingruber, F. D., Eckstein, F. Serre-Bachet, and O. U. Bräker. (1990). Identification, presentation, and interpretation of event years and pointer years in dendrochronology. *Dendrochronologia, 8*, 9–38.

Shanks, R. E. (1954). Climates of the Great Smoky Mountains. *Ecology*, *35*, 354–361.

Shroder, J. F. (1978). Dendrogeomorphological analysis of mass movement on Table Cliffs Plateau, Utah. *Quaternary Research, 9*(2), 168–185.

Shroder, J. F. (1980). Dendrogeomorphology: review and new techniques of tree-ring dating. *Progress in Physical Geography, 4*(2), 161–188.

Siccama, T. G., G. M. Bliss, and H. W. Vogelmann. (1982). Decline of red spruce in the Green Mountains of Vermont. *Bulletin Torrey Botanical Club*, *109*, 162–168.

Sigafoos, R. S. (1964). Botanical evidence of floods and flood-plain deposition. USGS *Professional Paper 485*A, 1–35

Sigafoos, R. S. and E. L. Hendricks. (1961). Botanical evidence of the modern history of Nisqually Glacier, Washington. USGS *Professional Paper* 387-A.

Slayton, J. D. (2010). Separating the Effects of Wildfires from Climate in Growth of Ponderosa Pine (Pinua ponderosa Douglas ex. C. Lawson), Central Idaho, U.S.A. Master's Thesis, The University of Tennessee, Knoxville.

Solomina, O. N. (2002). Dendrogeomorphology-research requirements. *Dendrochronologia*, *20*(1-2), 233–245.

Soulé, P. T. (2011). Changing climate, atmospheric composition, and radial tree growth in a spruce-fir ecosystem on Grandfather Mountain, North Carolina. *Natural Areas Journal*, *31*(1), 65–74.

Speer, J.H. 2001. Oak mast history from dendrochronology: a new technique demonstrated in the southern Appalachian region. PhD dissertation, University of Tennessee, Knoxville.

Speer, J. H. (2010). *Fundamentals of Tree-Ring Research*. Tucson: University of Arizona Press.

Stoffel, M., and M. Bollschweiler. (2008). Tree-ring analysis in natural hazards research; an overview. *Natural Hazards and Earth System Sciences, 8*(2), 187–202.

Stoffel, M., and M. Bollschweiler. (2009). What tree rings can tell about earth-surface processes: Teaching the principles of dendrogeomorphology. *Geography Compass, 3*(3), 1013–1037.

Stokes, M. A. and T. L. Smiley. (1996). *Introduction to Tree-Ring Dating*. Tucson: University of Arizona Press.

Swetnam, T. W., M. A. Thompson, and E. K. Sutherland. (1985). Using dendrochronology to measure radial growth of defoliated trees. *Spruce Budworms Handbook:* USDA *Agriculture Handbook No. 639*.

The Plant List. (2010). Version 1. Published on the Internet; http://www.theplantlist.org/ Accessed 12/18/2013.

Varnes, D.J. (1978). Slope movement types and processes. In: *Special Report 176: Landslides: Analysis and Control* (Eds: Schuster, R. L. & Krizek, R. J.). Transportation and Road Research Board, National Academy of Science, Washington D. C., 11–33.

White, P. B. (2010). Decadal-Scale Trends in Forest Succession and Climatic Sensitivity in a Red Spruce-Fraser Fir Forest at Roan Mountain, Pisgah and Cherokee National Forests. Master's Thesis. The University of Tennessee, Knoxville.

White, P. B., P. Soule, and S. van de Gevel. (2013). Impacts of human disturbance on the temporal stability of climate-growth relationships in a red spruce forest, southern Appalachian Mountains, USA. *Dendrochronologia*. http://dx.doi.org/10.1016./j.dendro.2013.10.001. Accessed 1/27/2013.

White, P. B., S. L. van de Gevel, and P. T. Soulé. (2012). Succession and disturbance in an endangered red spruce-Fraser fir forest in the southern Appalachian Mountains, North Carolina, USA. *Endangered Species Research*, *18*, 17–25.

White, P. S., M. D. Mackenzie, and R. T. Busing. (1985). Natural disturbance and gap phase dynamics in southern Appalachian spruce-fir forests. *Canadian Journal of Forest Research*, *15*(1), 233–240.

Whittaker, R. H. (1956). Vegetation of the Great Smoky Mountains. *Ecological Monographs*, *26*(1), 1–80.

Wieczorek, G. F., and B. A. Morgan, (2008), Debris-flow hazards within the Appalachian Mountains of the Eastern United States: U.S. Geological Survey Fact Sheet 2008–3070, 4 p., http://pubs.usgs.gov/fs/2008/3070/ Accessed 12/13/2013.

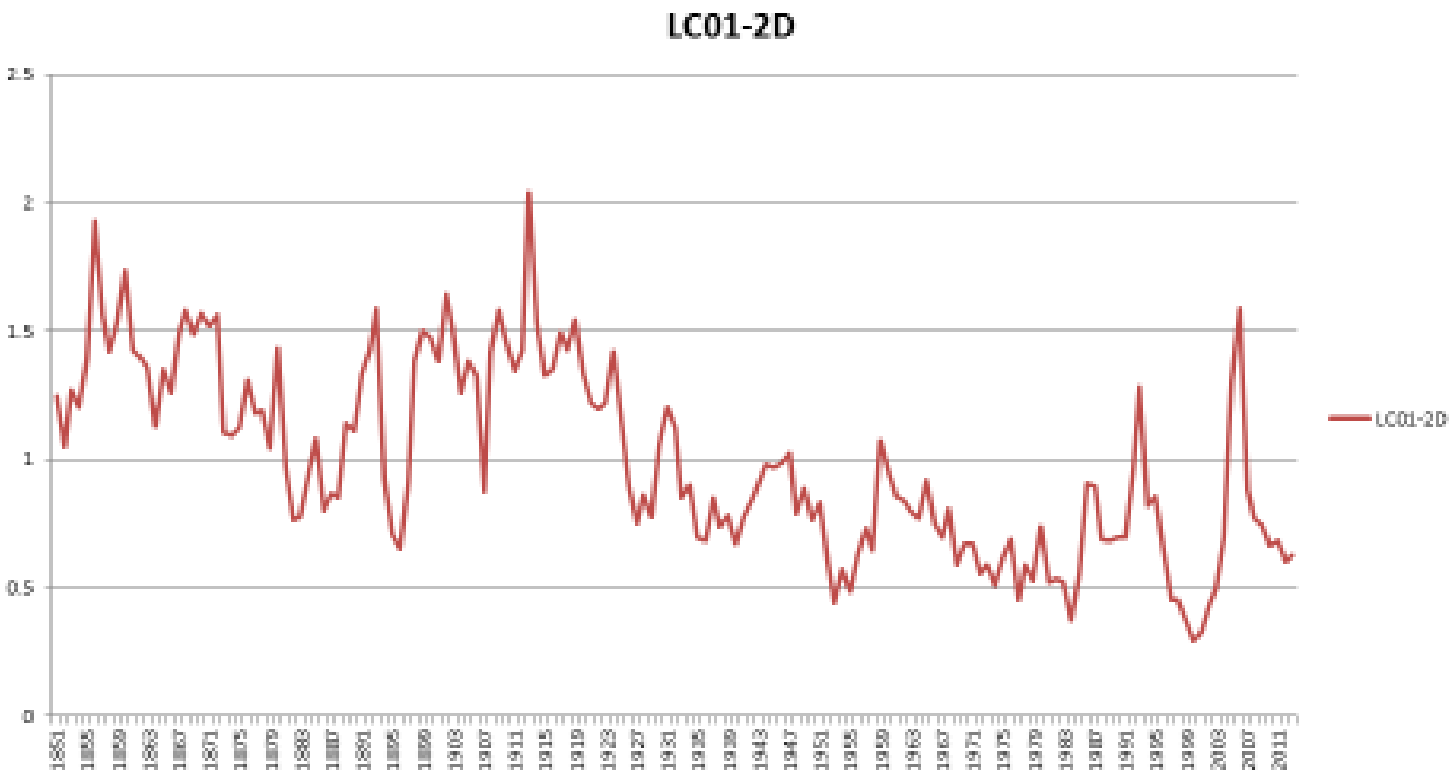
Wise, K. and R. Petersen. (1998). *A Natural History of Mount Le Conte*. Knoxville, Tennessee: University of Tennessee Press.

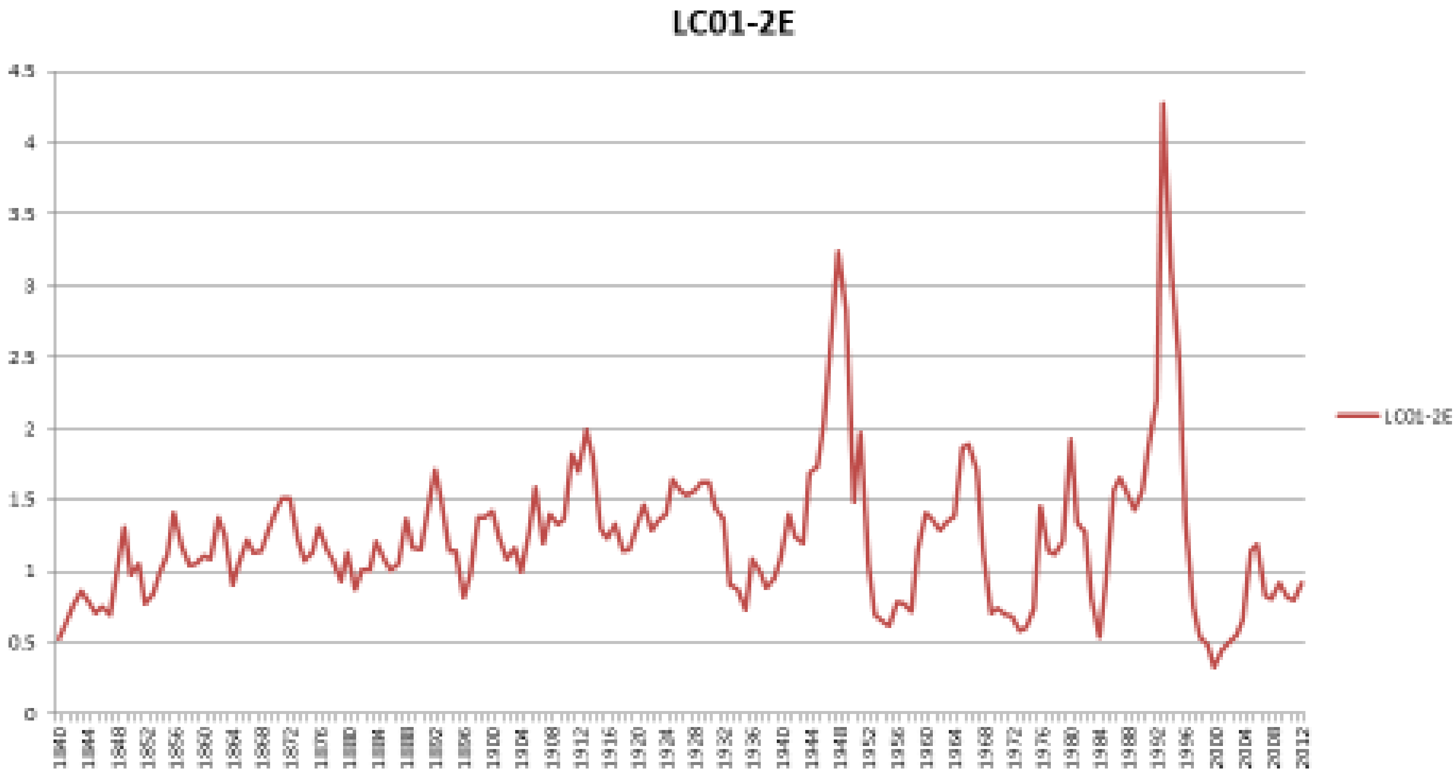
Zhang, Q. and R.I. Alfaro. (2003). Spatial synchrony of the two-year cycle budworm outbreaks in central British Colombia. *OIKOS*, 102, 146–154.

APPENDICES

Appendix 1: Line graphs and core scans for LC01 chronology

LC01-1C


LC01-2D
2.5
2
1.5
1
0.5
0
LC01-2D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4
3.5
3
2.5
2
1.5
1
0.5
0
1840
1844
1848
1852
1856
1860
1864
1868
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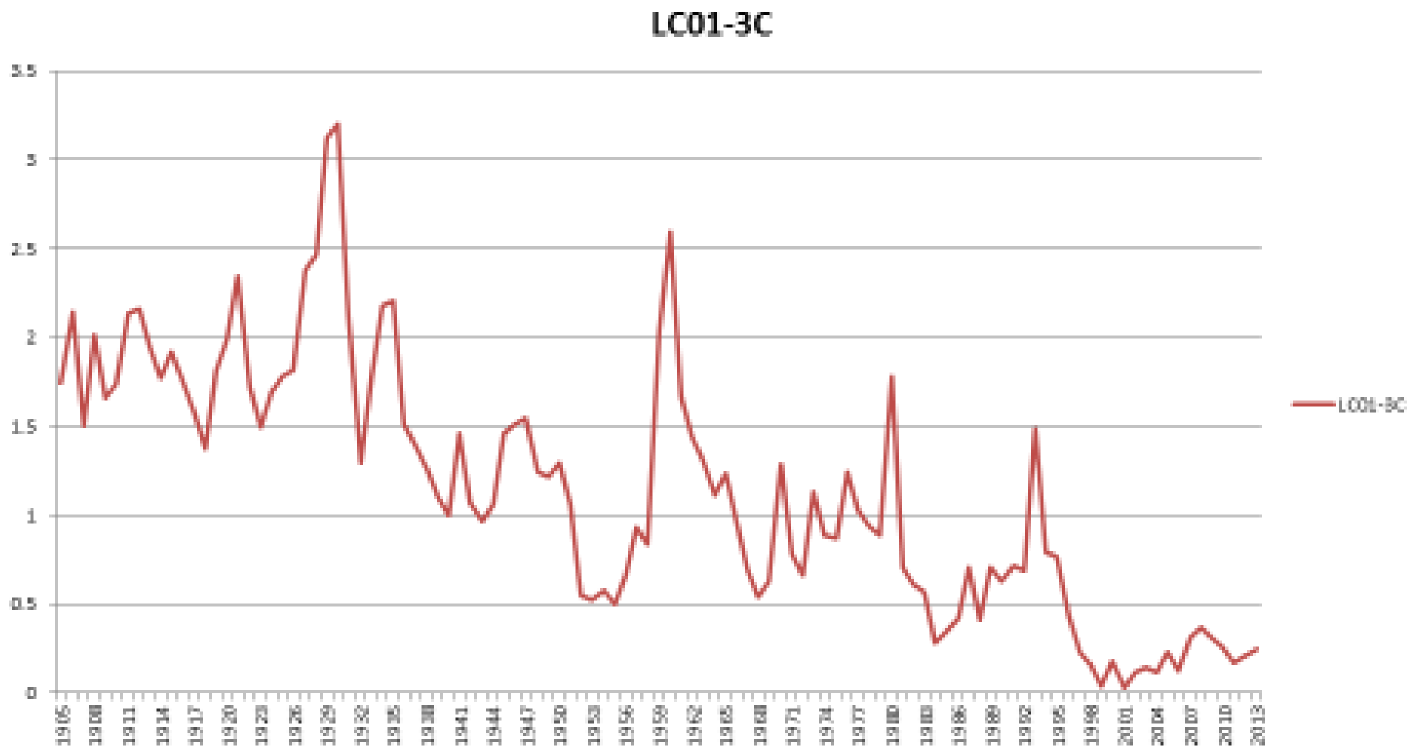
2004
2008
2012
LC01-2E


LC01-3C
3.5
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2.5
2
1.5
1
0.5
0
1905
1908
1911
1914
1917
1920
1923
1926
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1950
1953
1956
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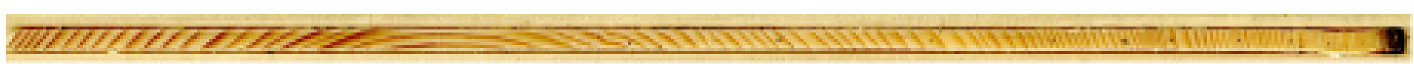

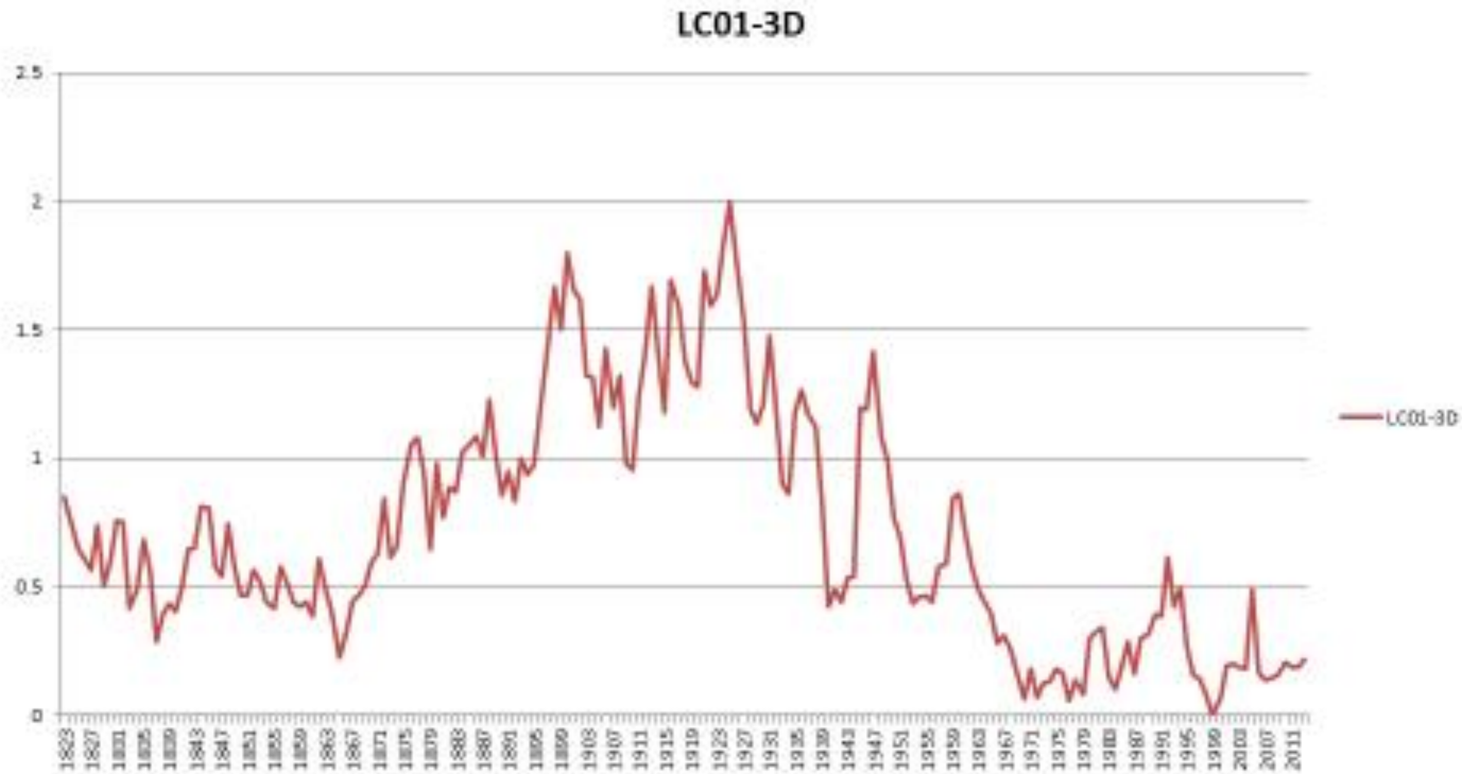
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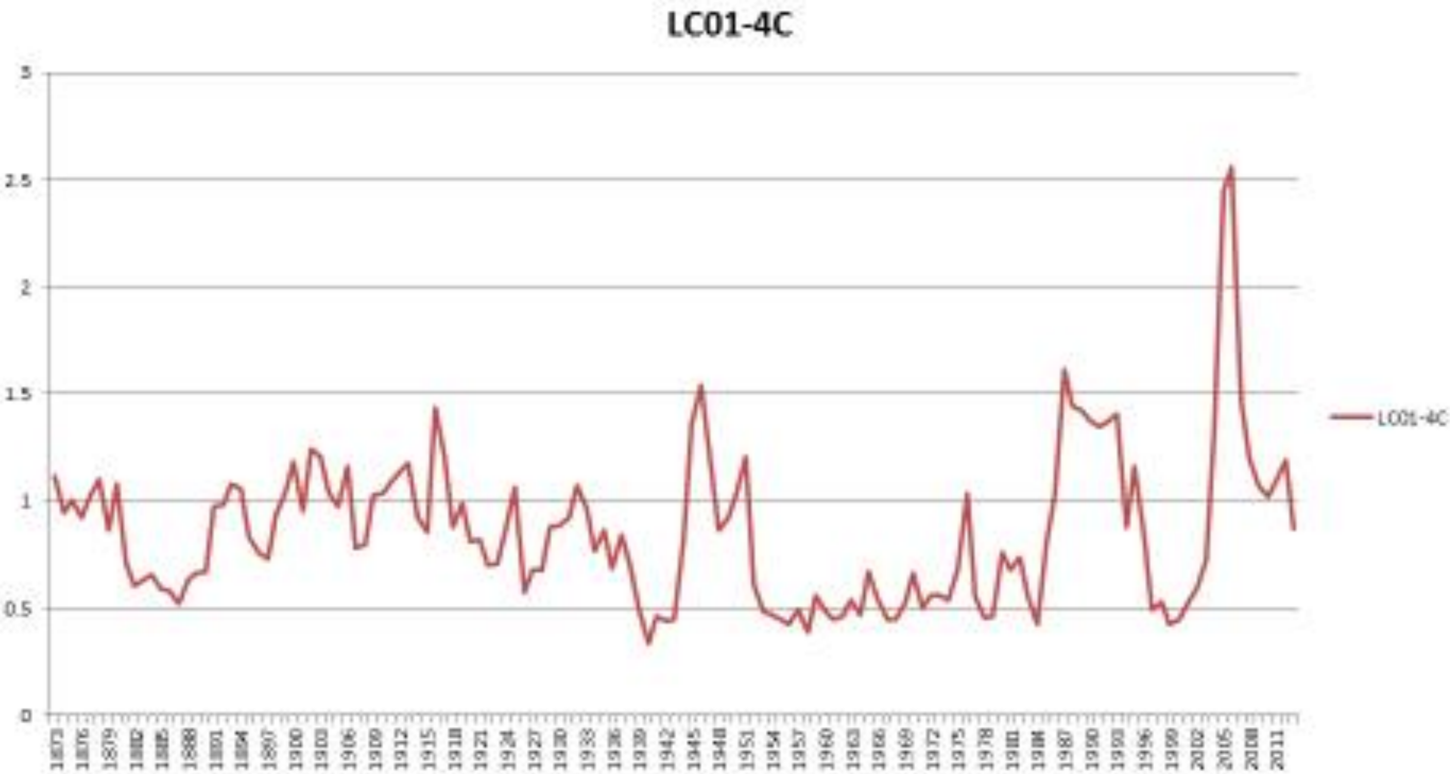
LC01-3D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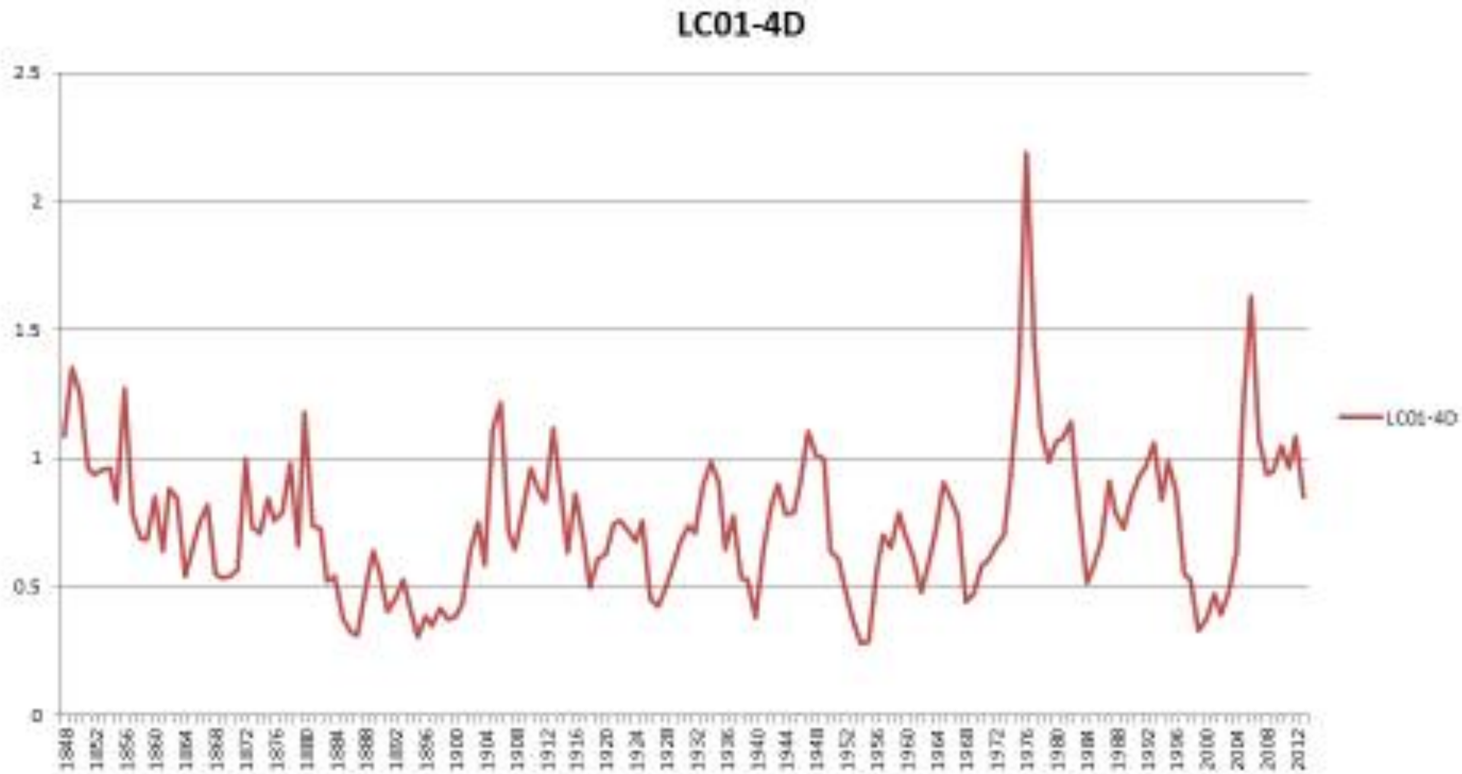
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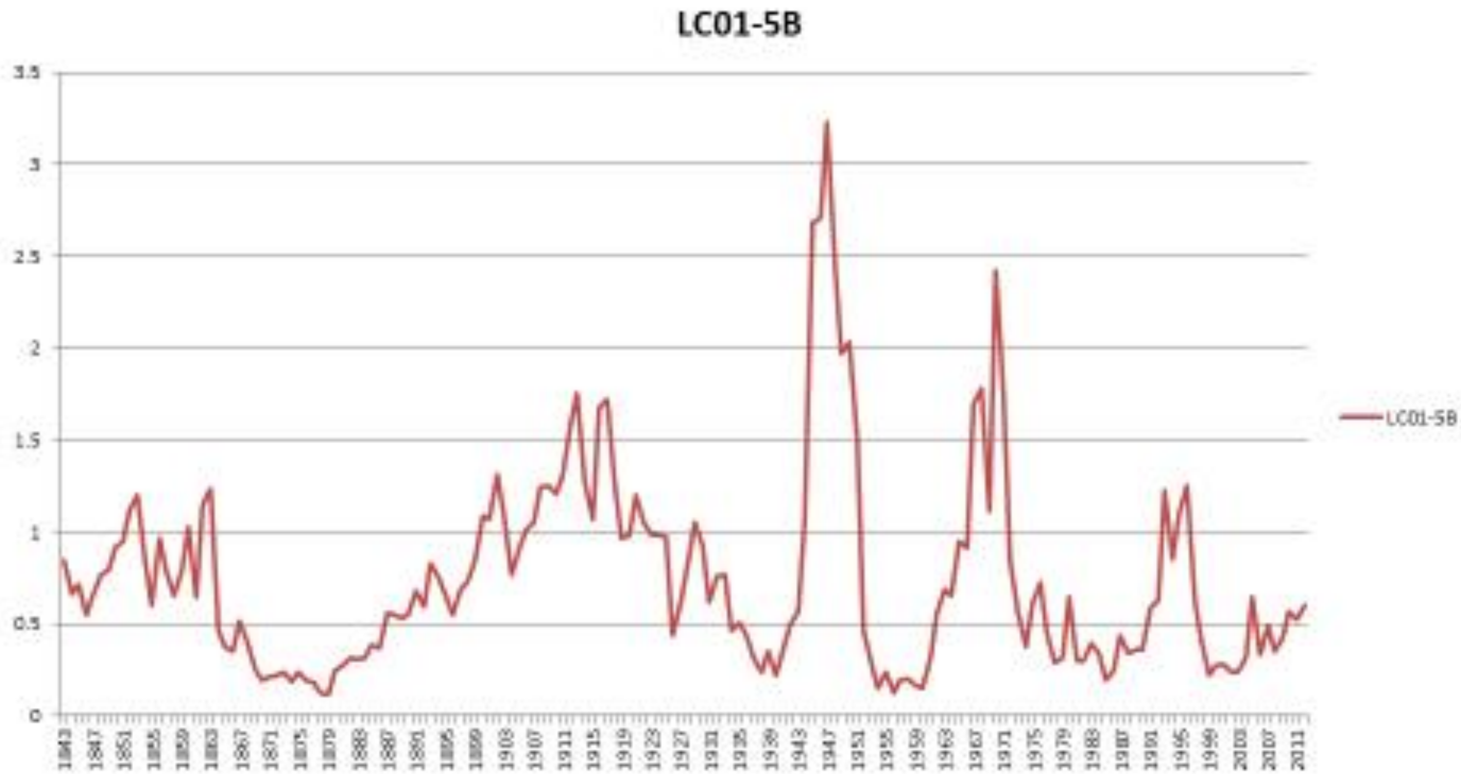
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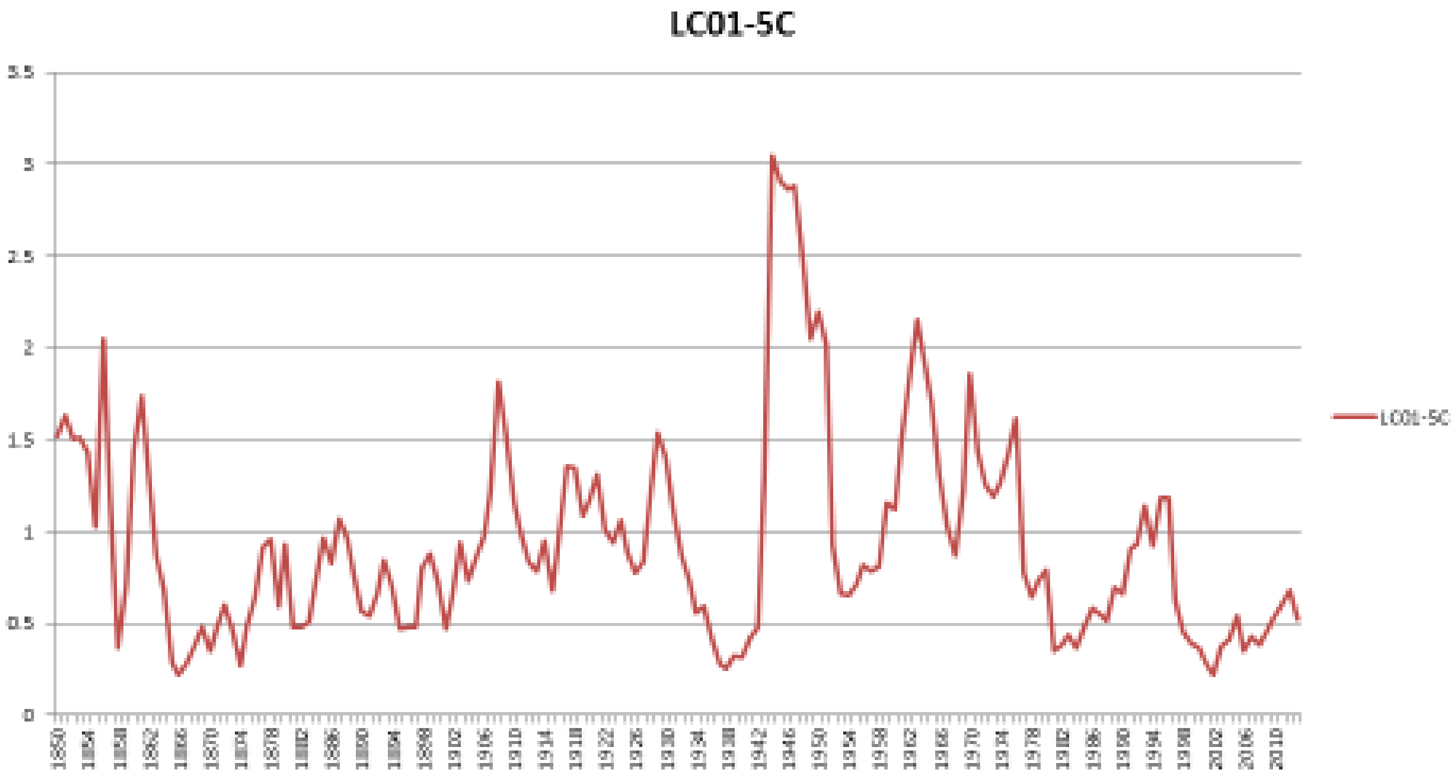
LC01-5B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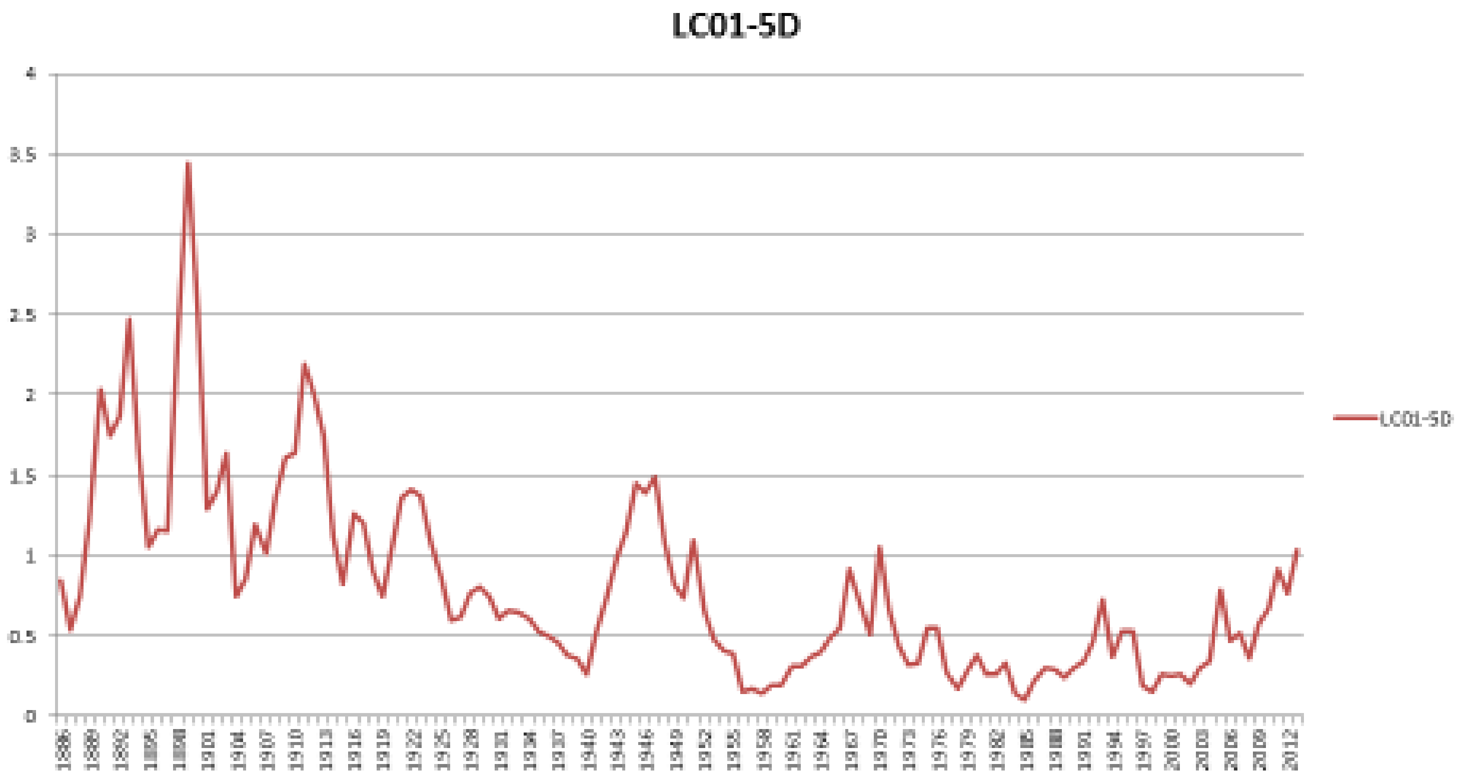
LC01-5C



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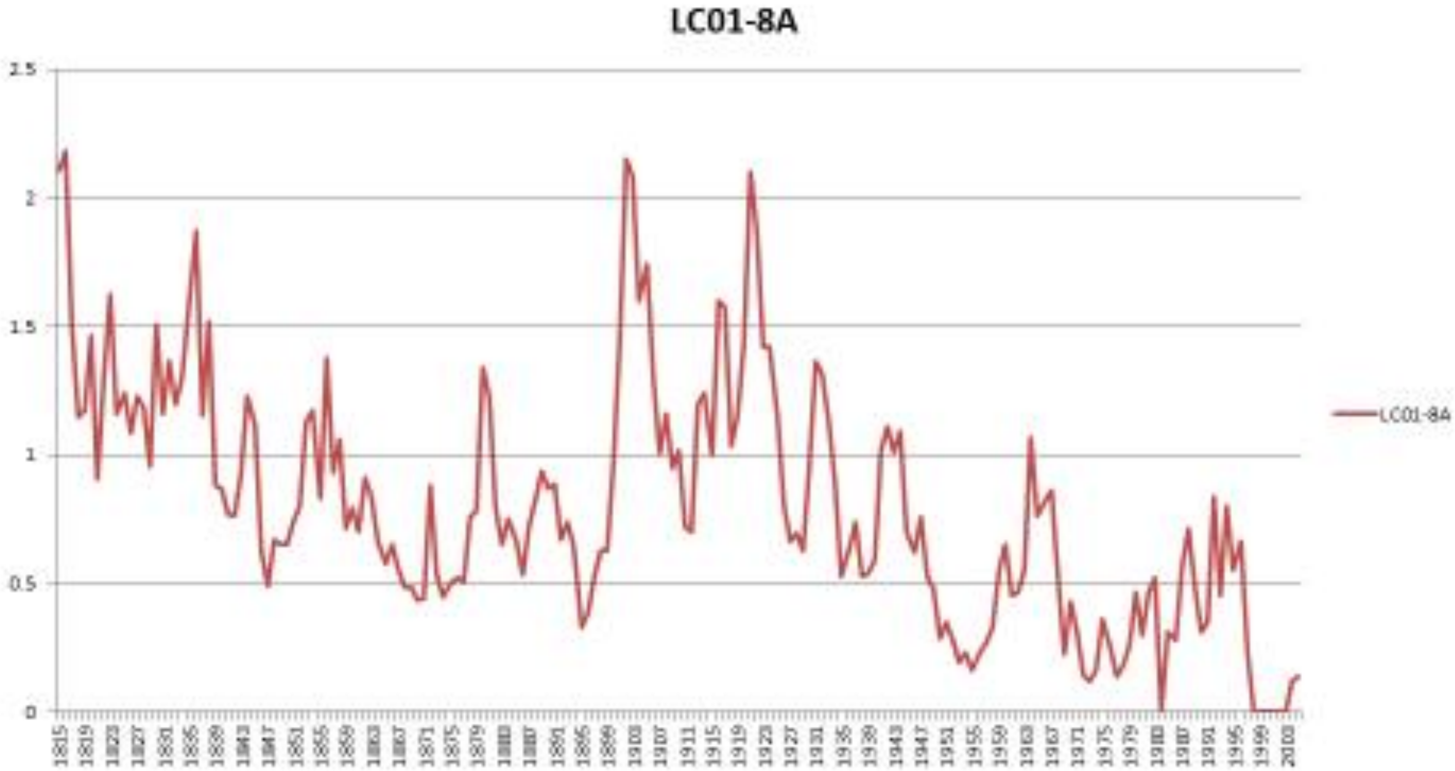
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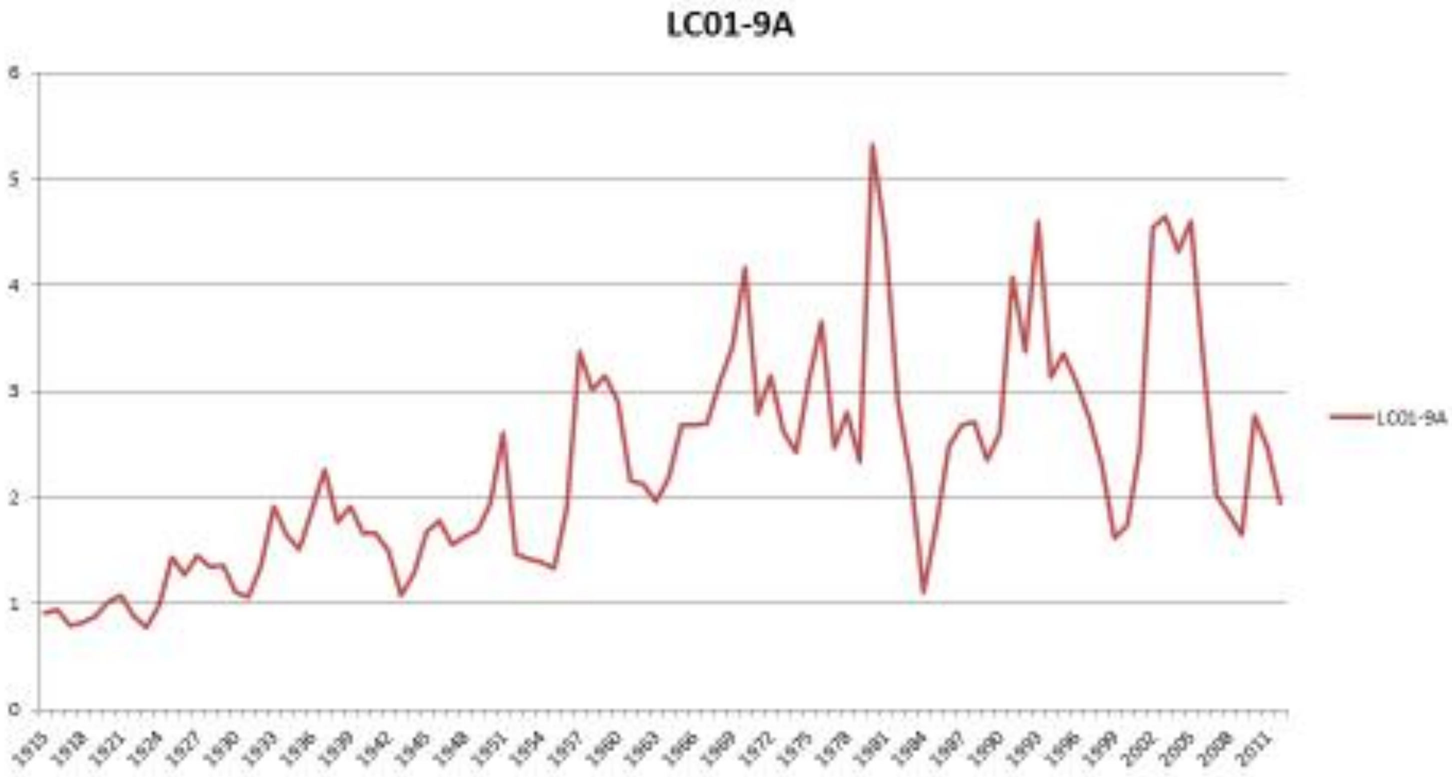
LC01-8A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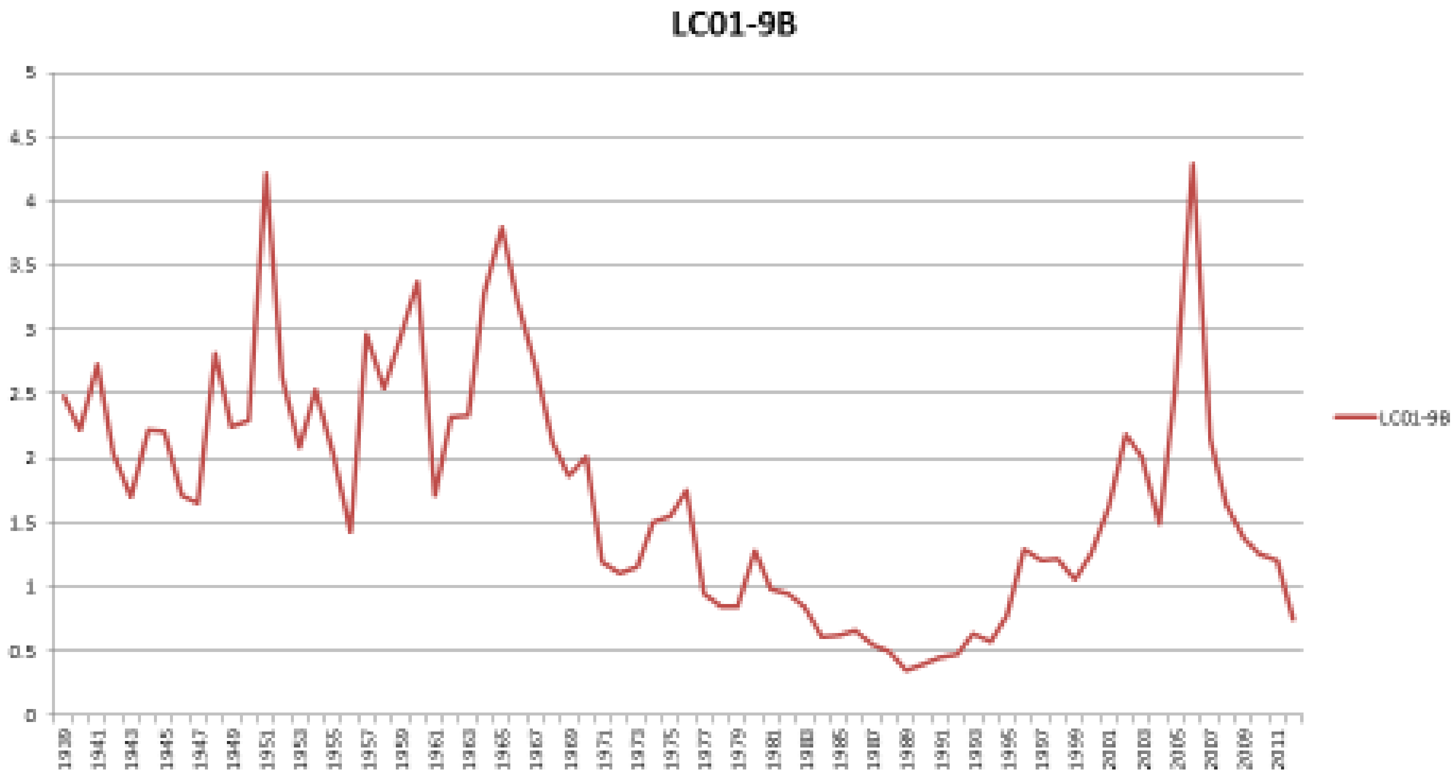
LC01-9A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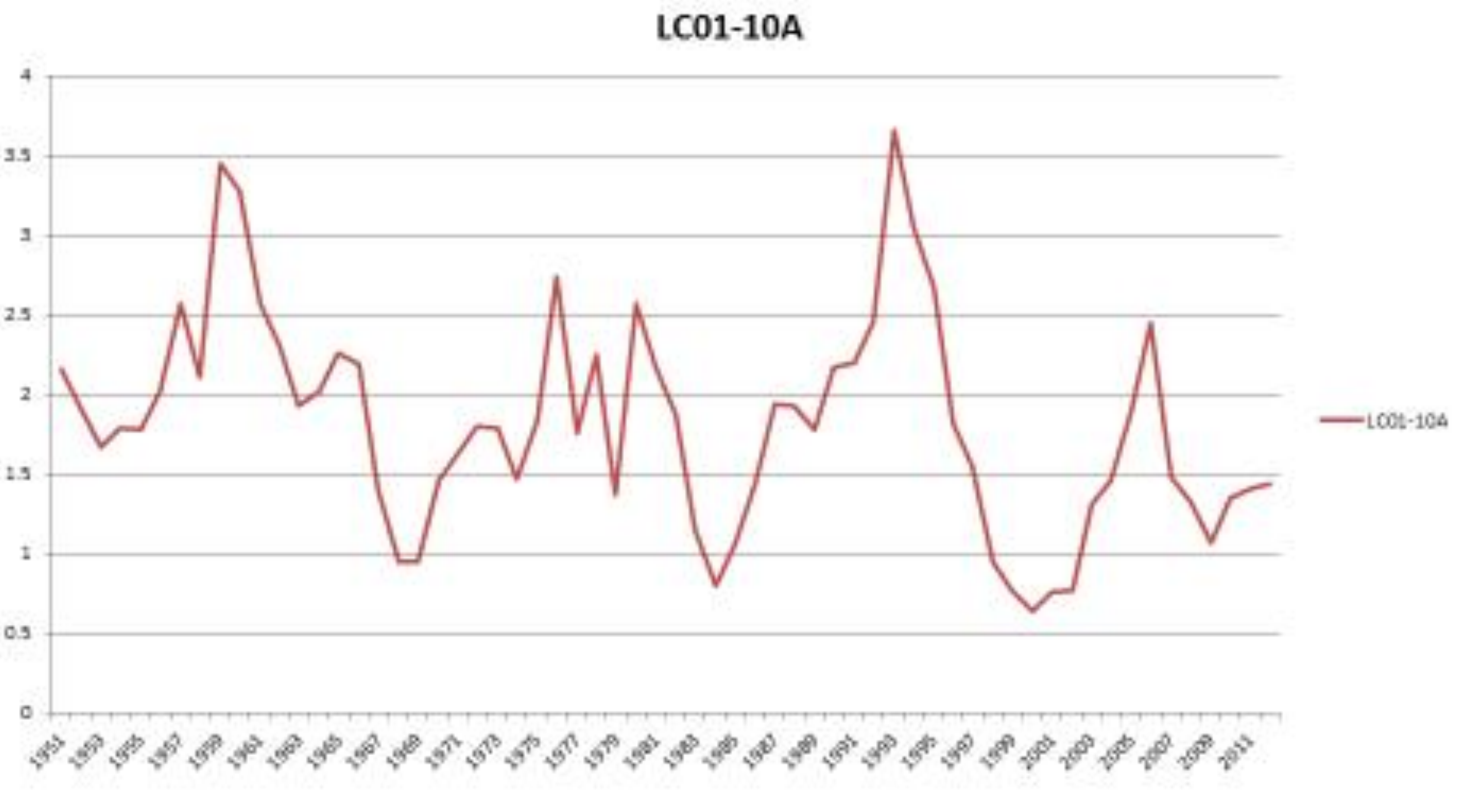
LC01-9B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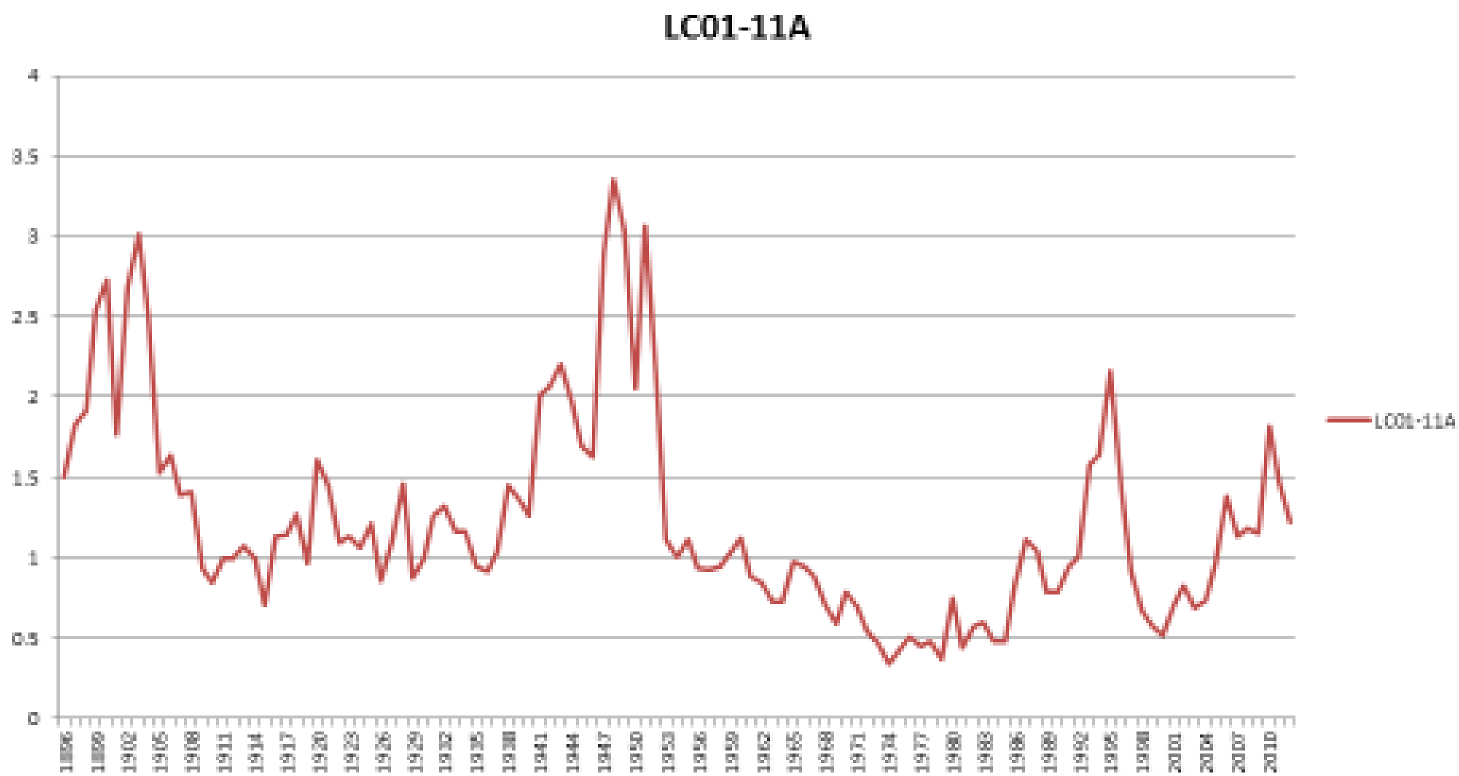
LC01-10A

LC01-10B


LC01-11A
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1950
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1962
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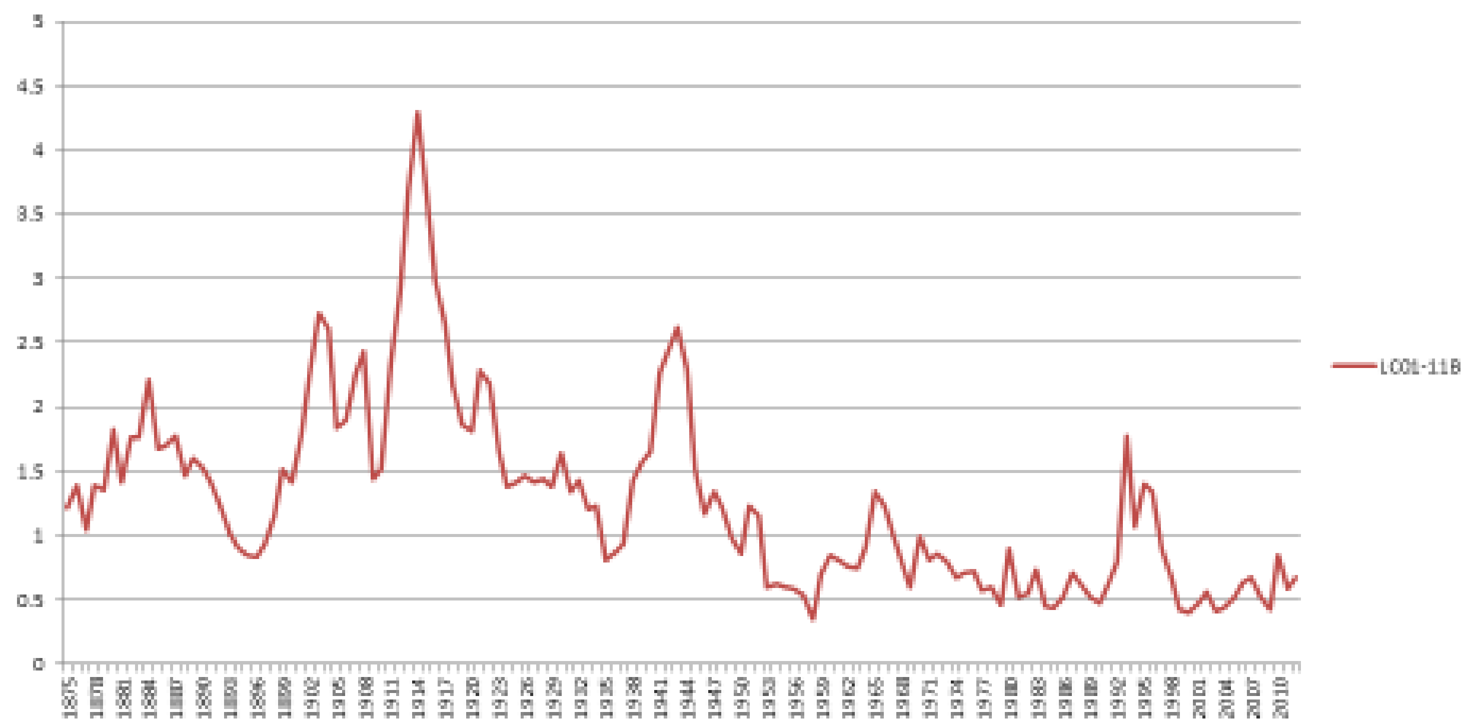
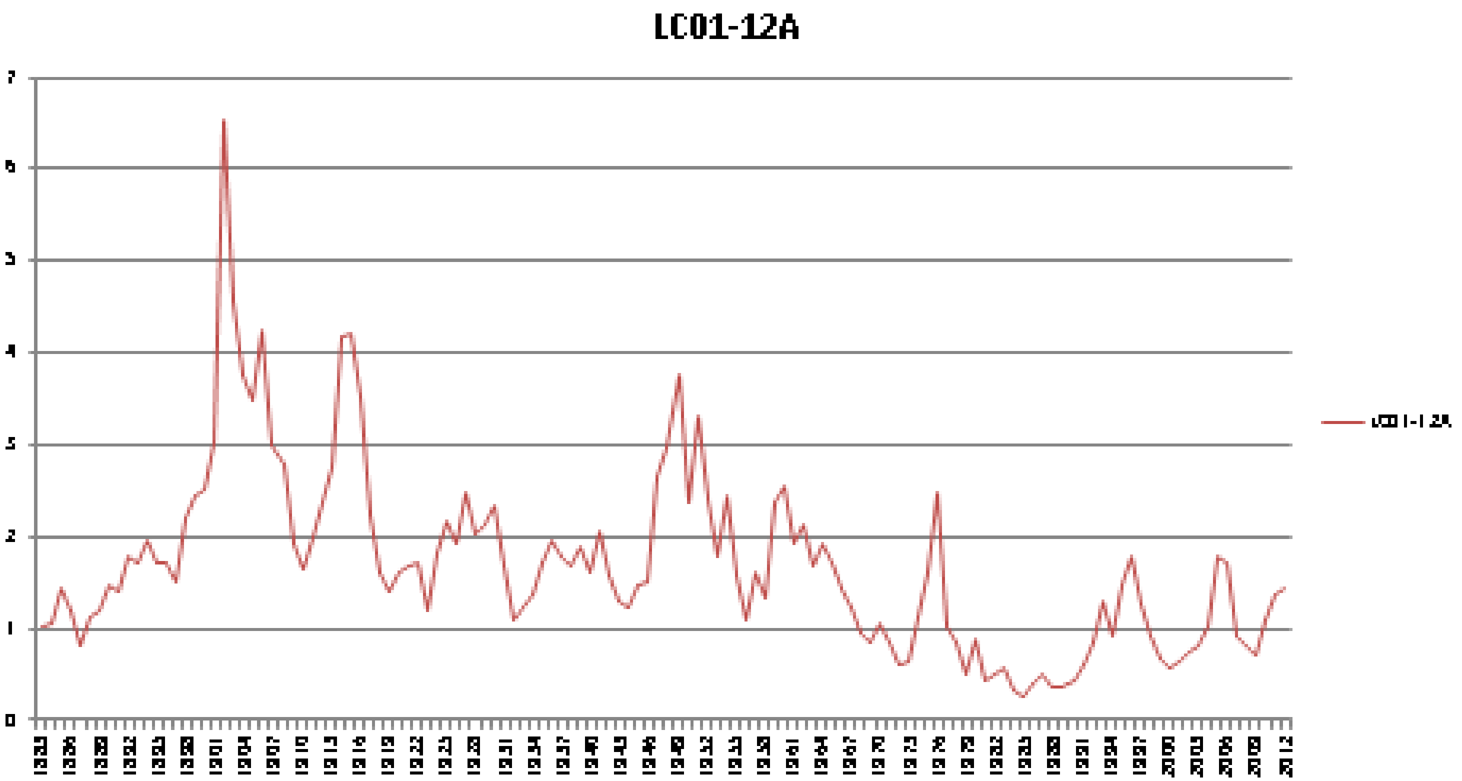
LC01-11A

LC01-11B

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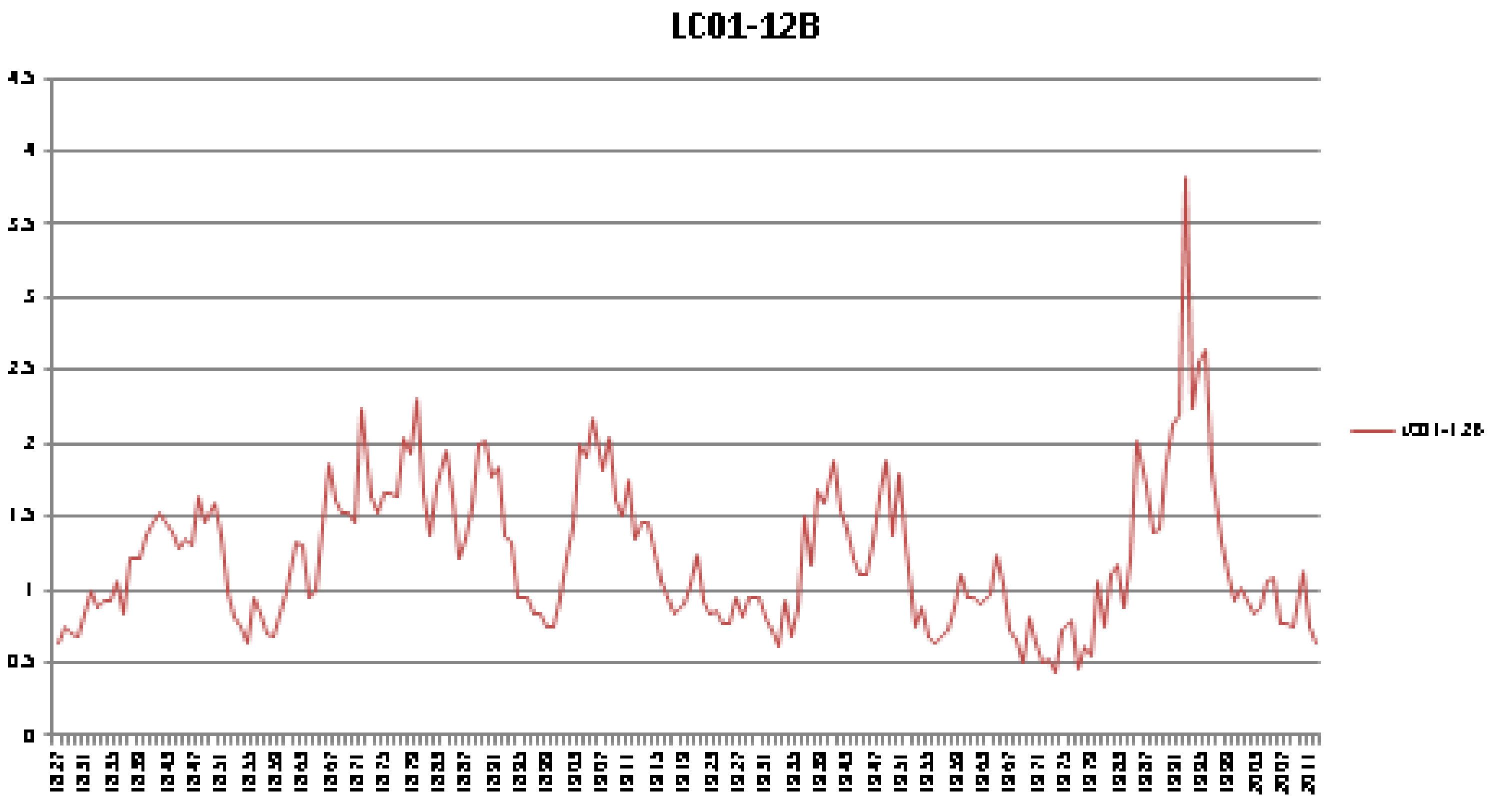
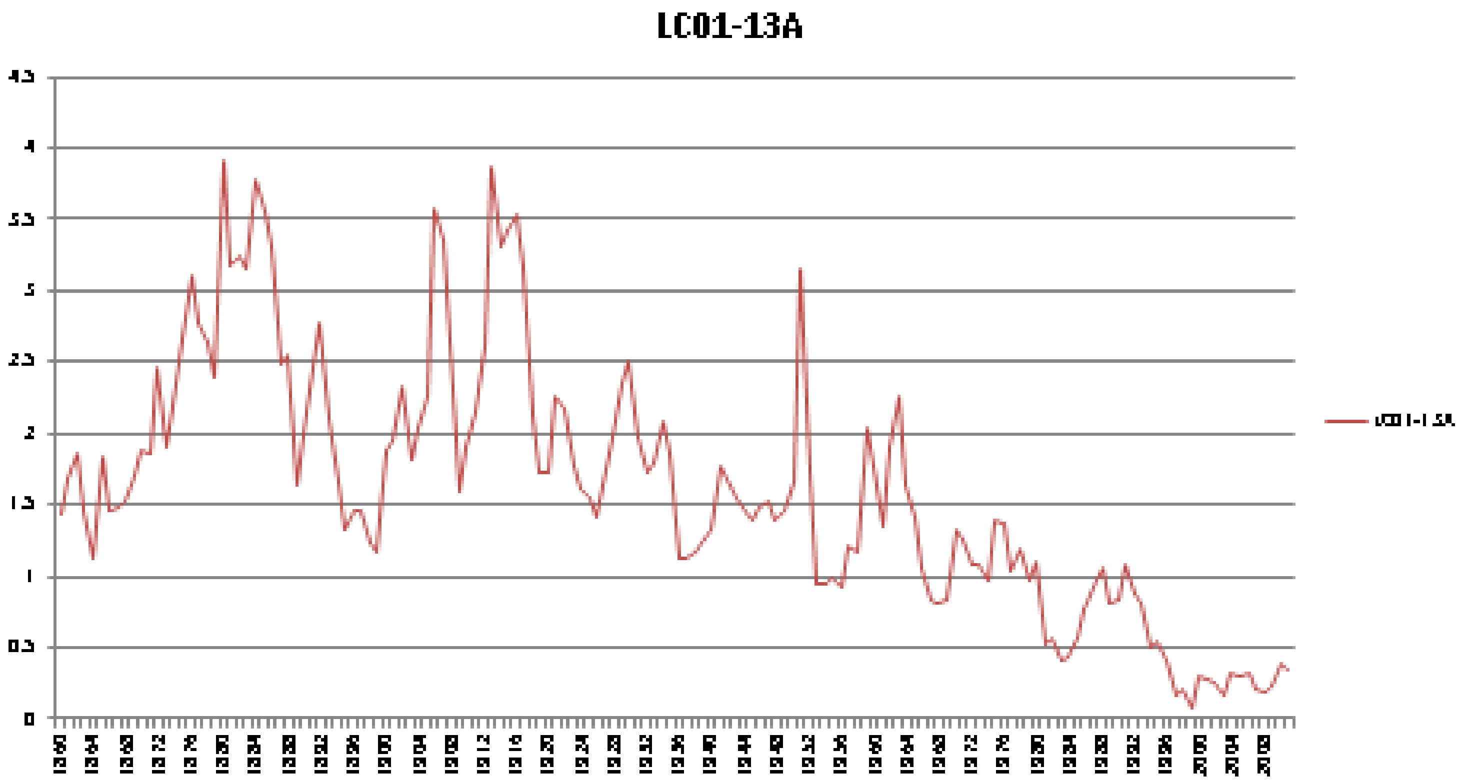
1
0


LC01-12B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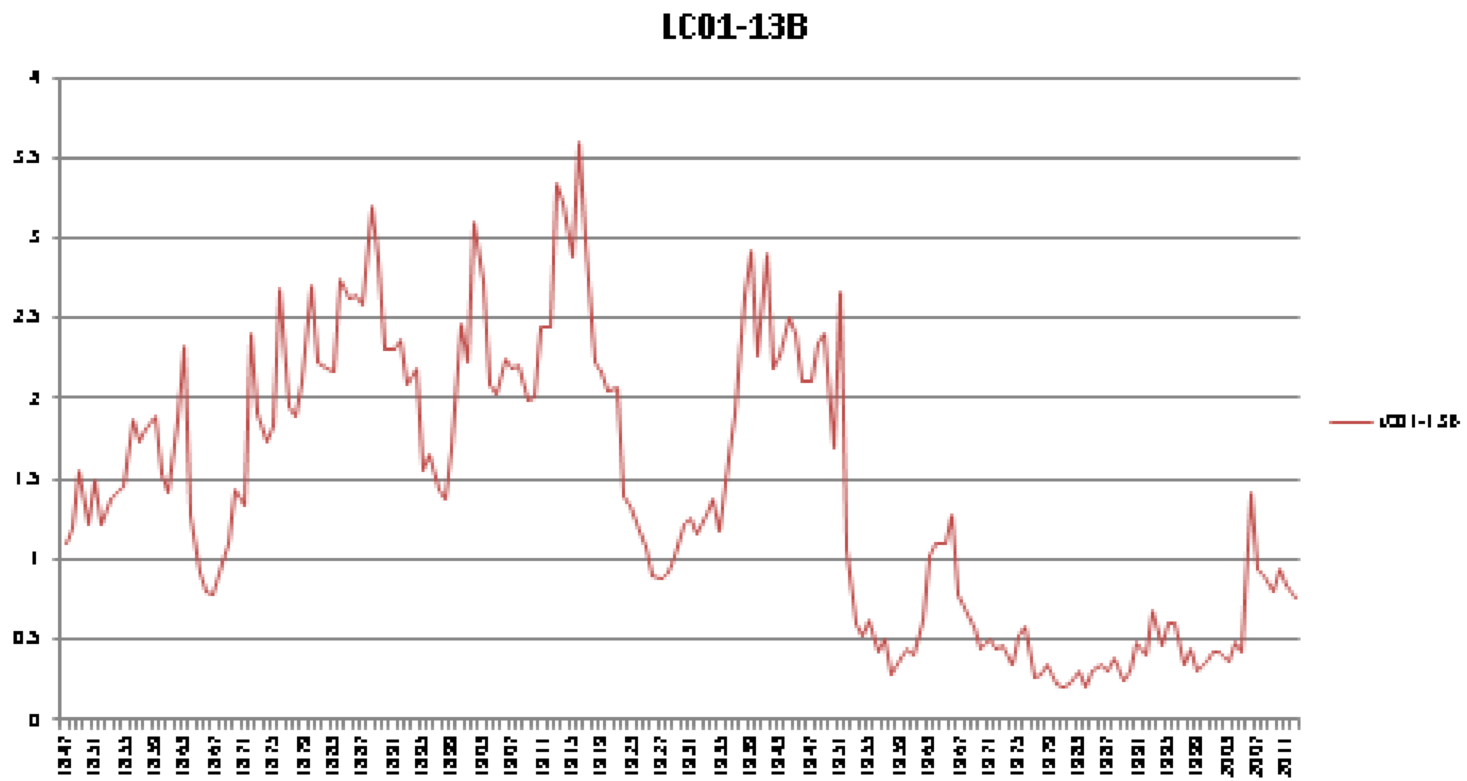
2.5
2
1.5
1
0.5
0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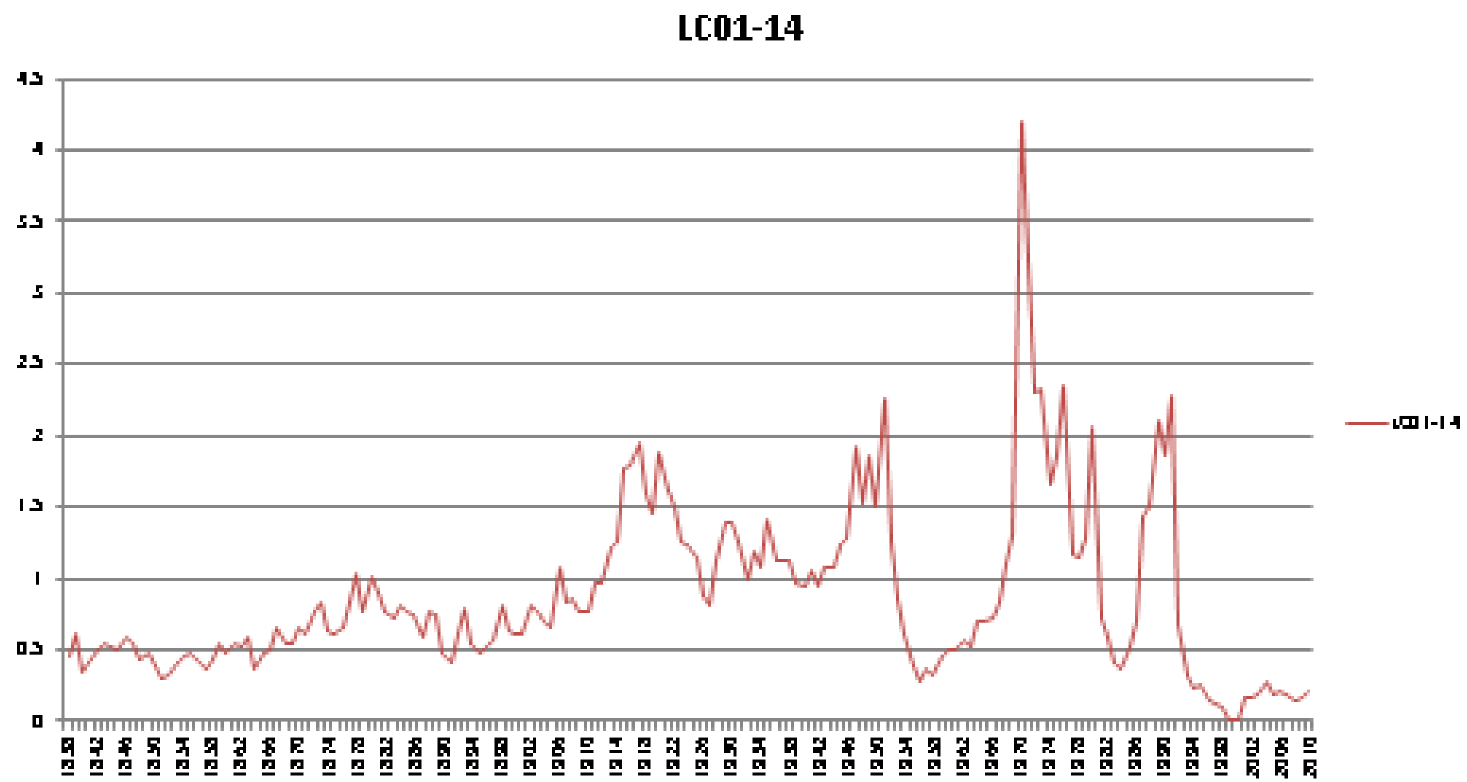
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2.5
2
1.5
1
0.5
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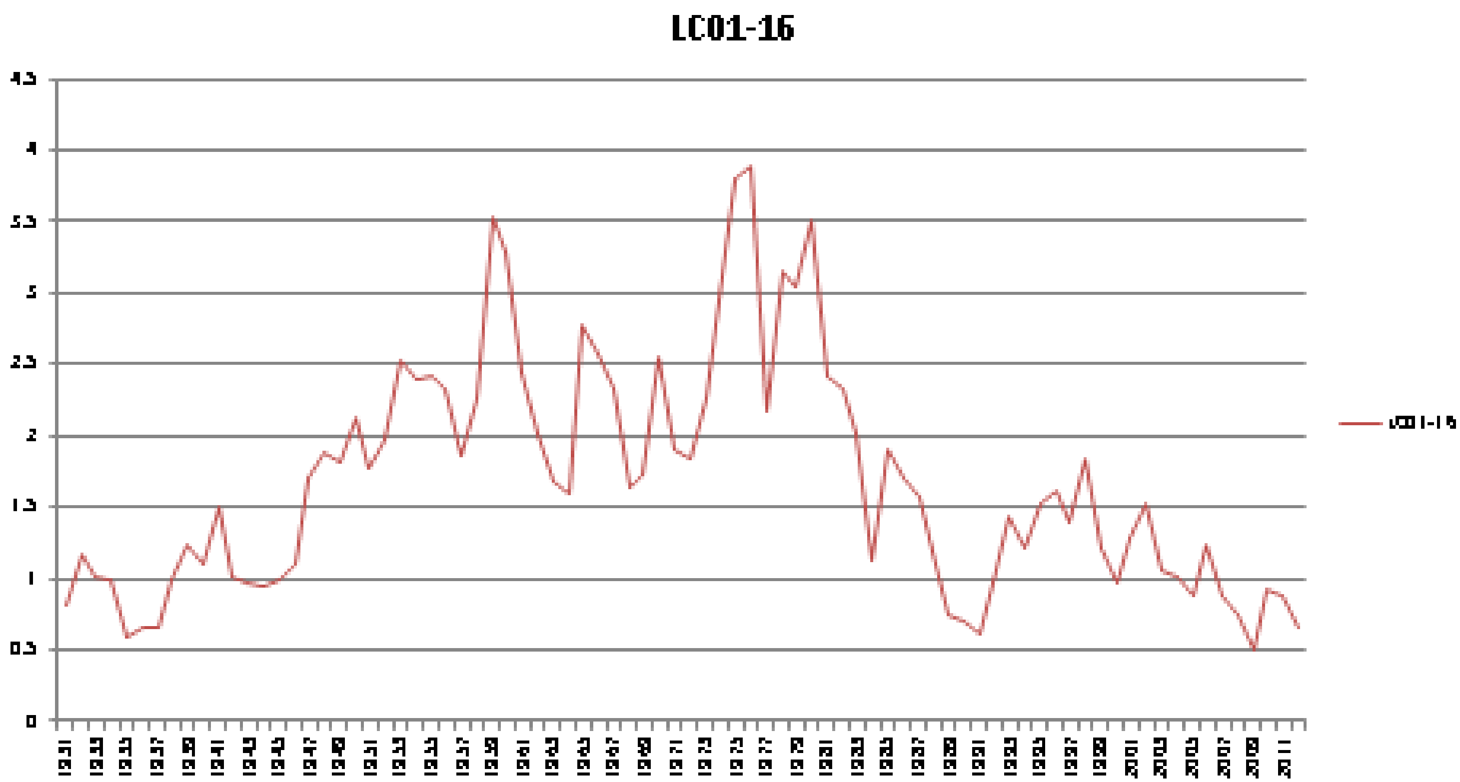
LC01-14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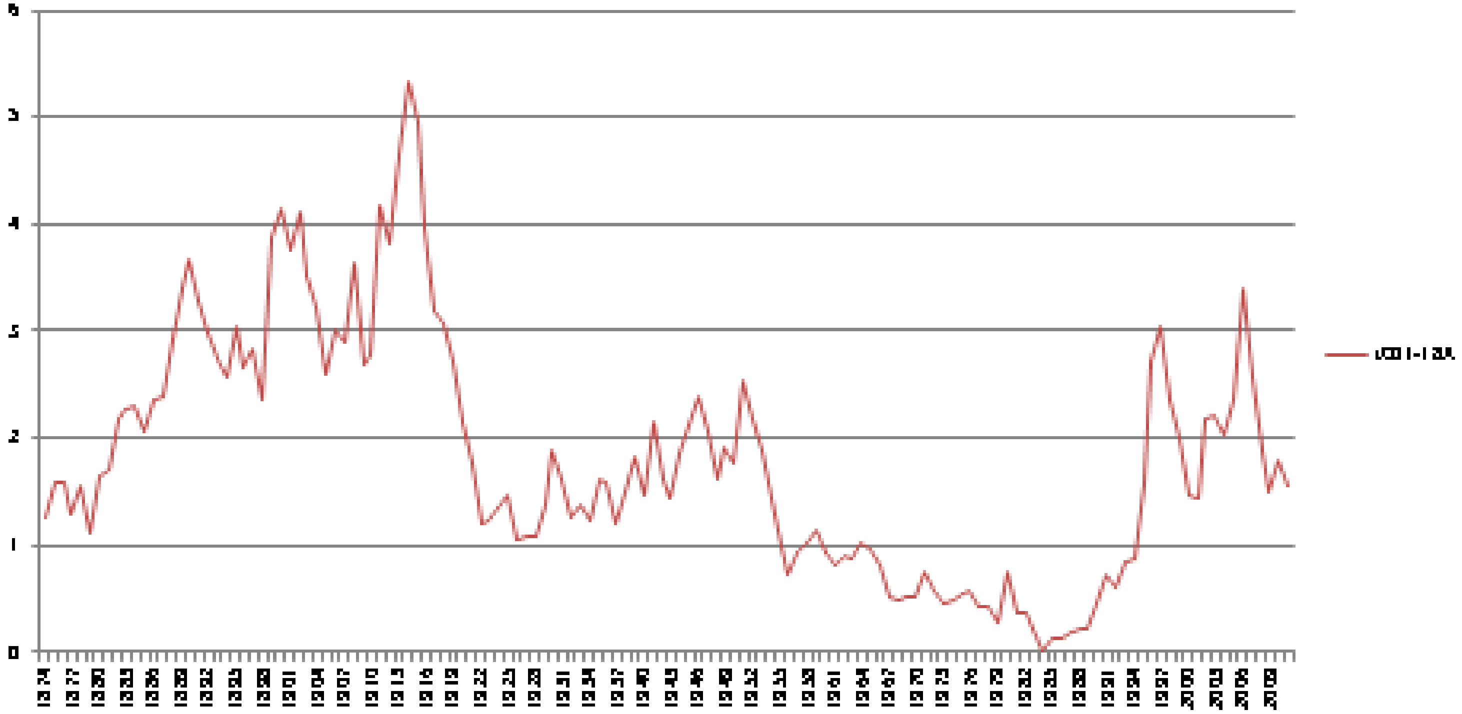
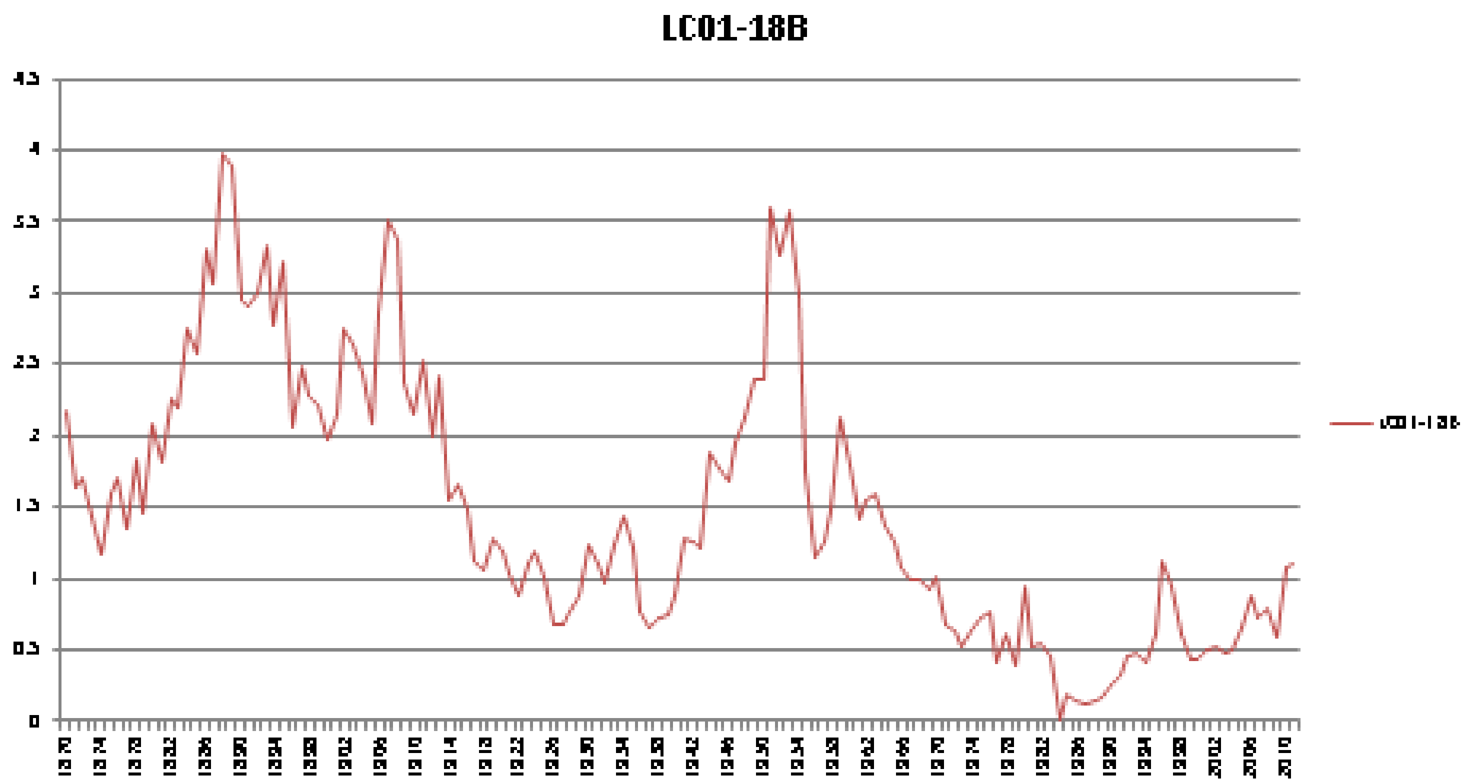
2.5
2
1.5
1
0.5
0

LC01-18A





LC01-18B
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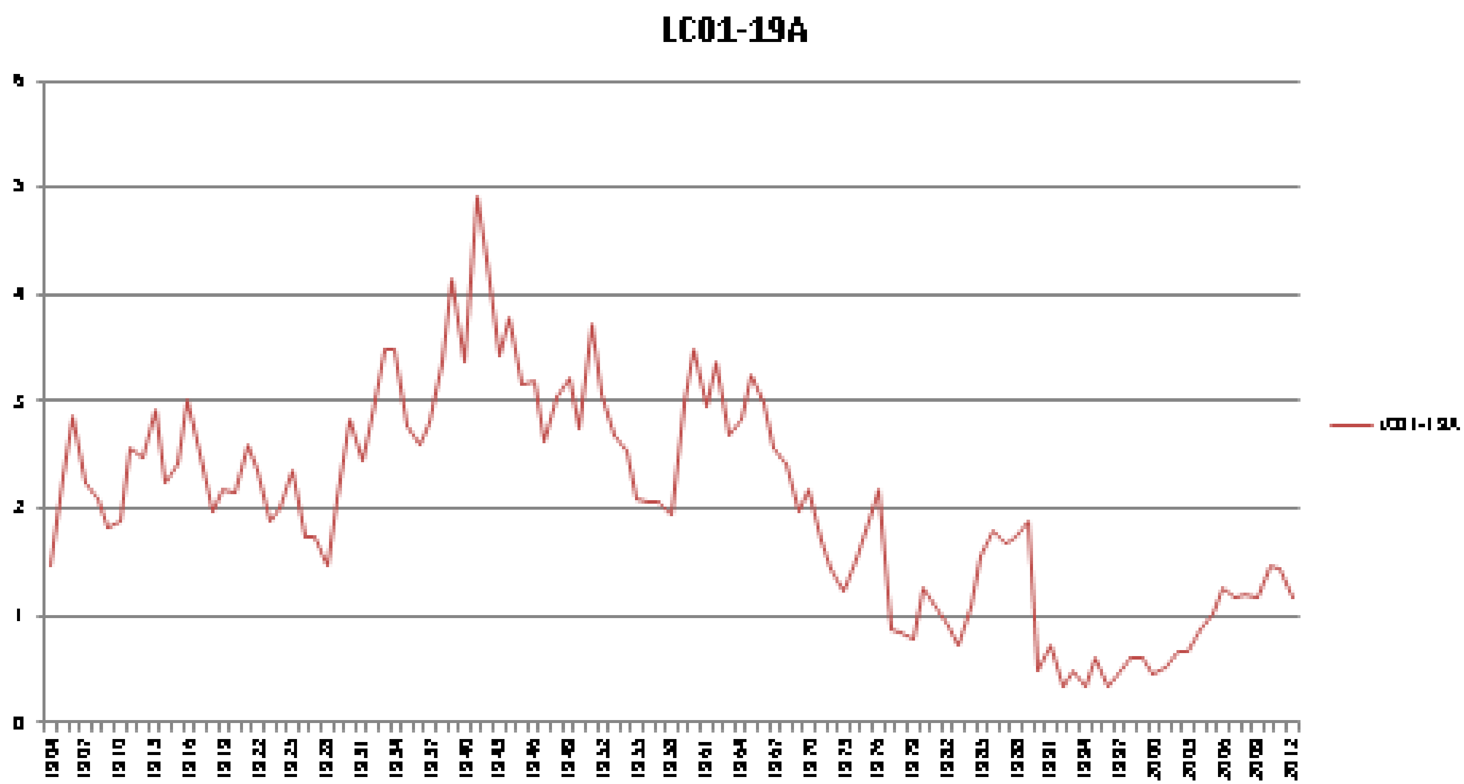
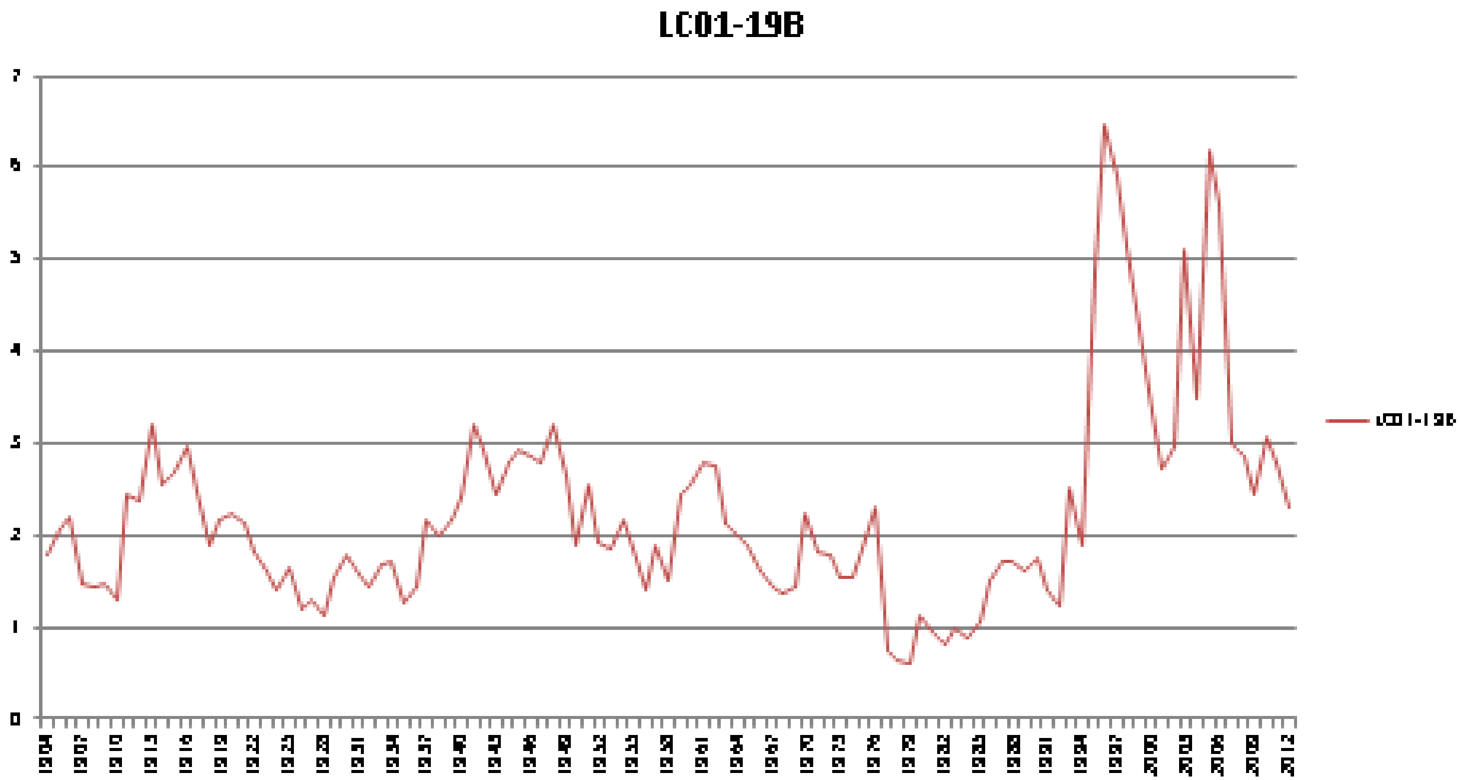
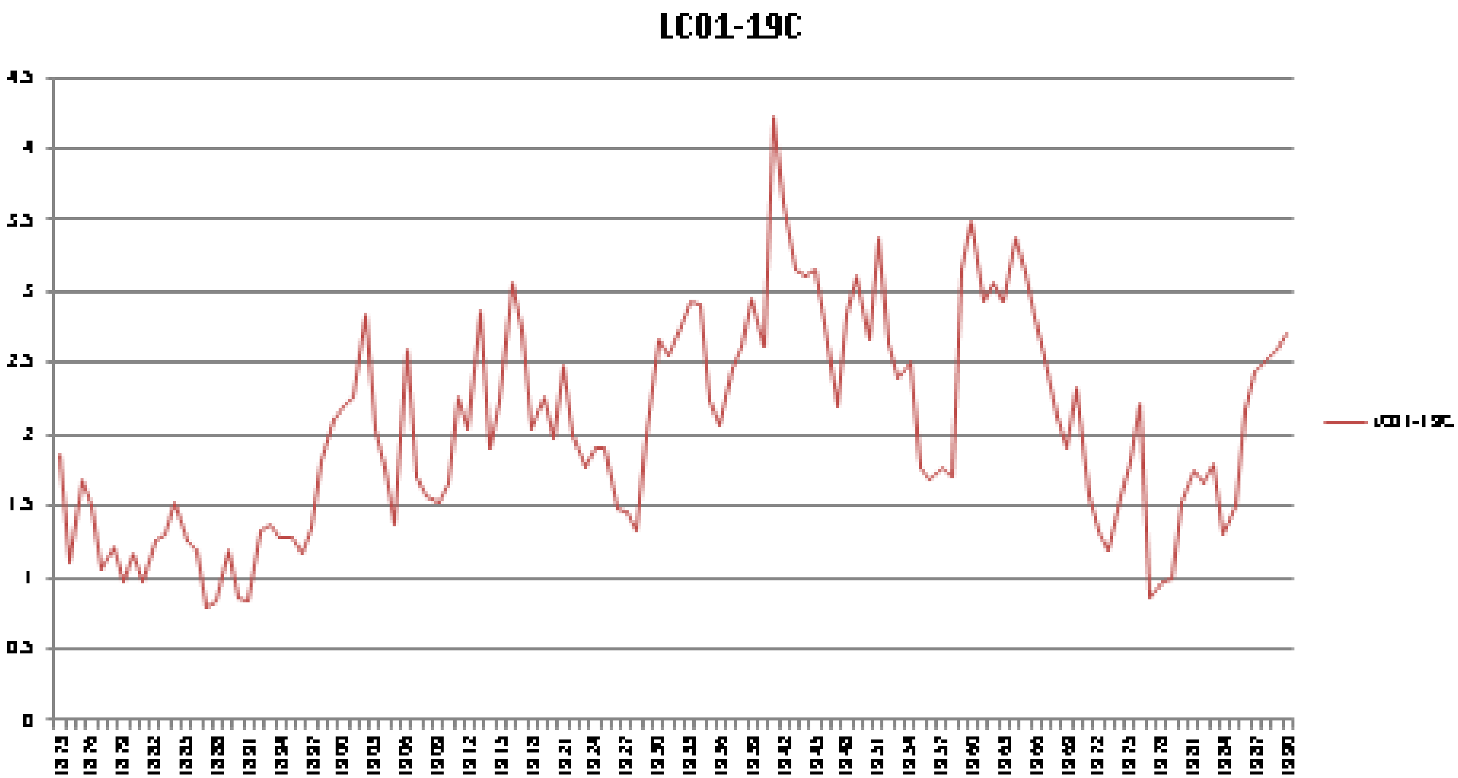
4
3.5
3
2.5
2
1.5
1
0.5
0


LC01-19A


LC01-19B
7
6
5
4
3
2
1
0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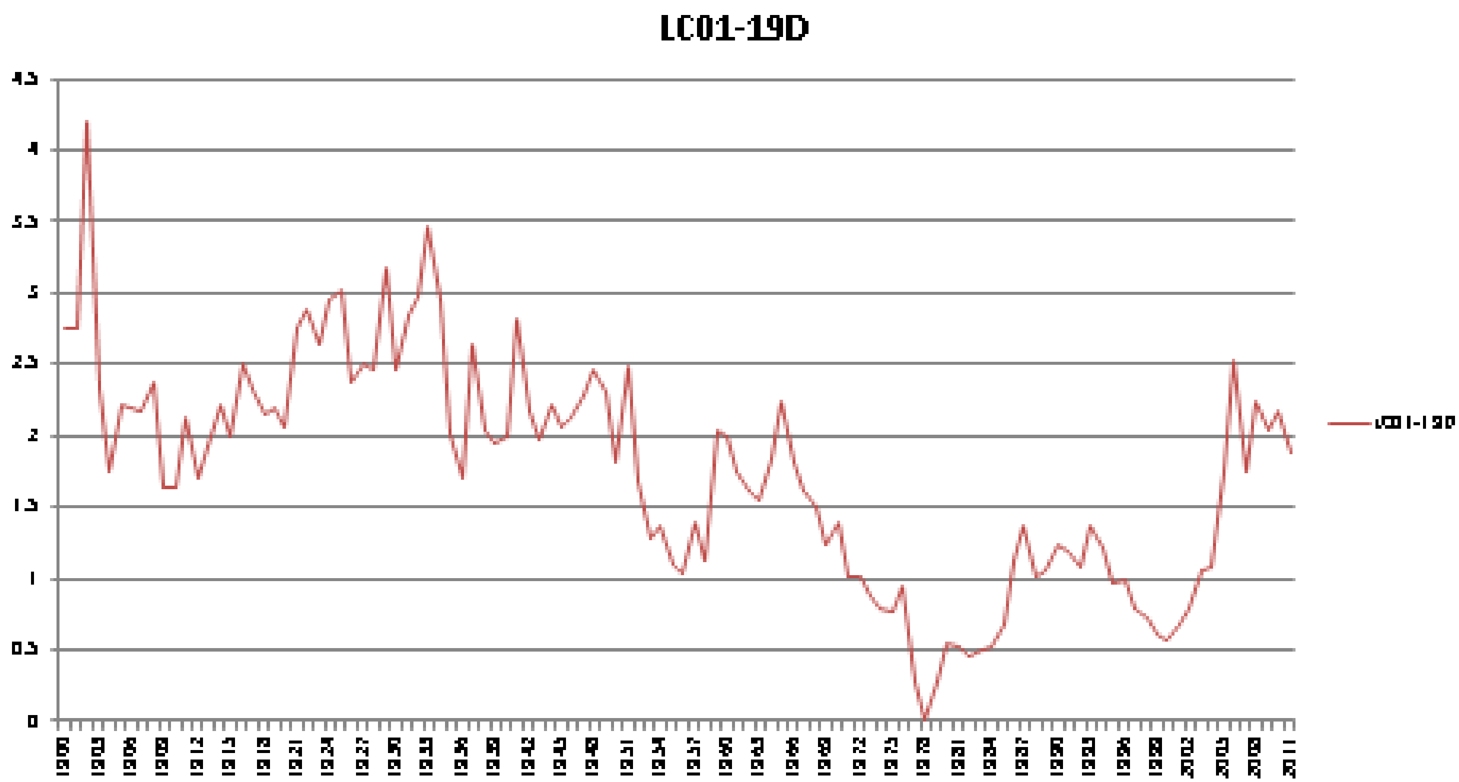
LC01-19C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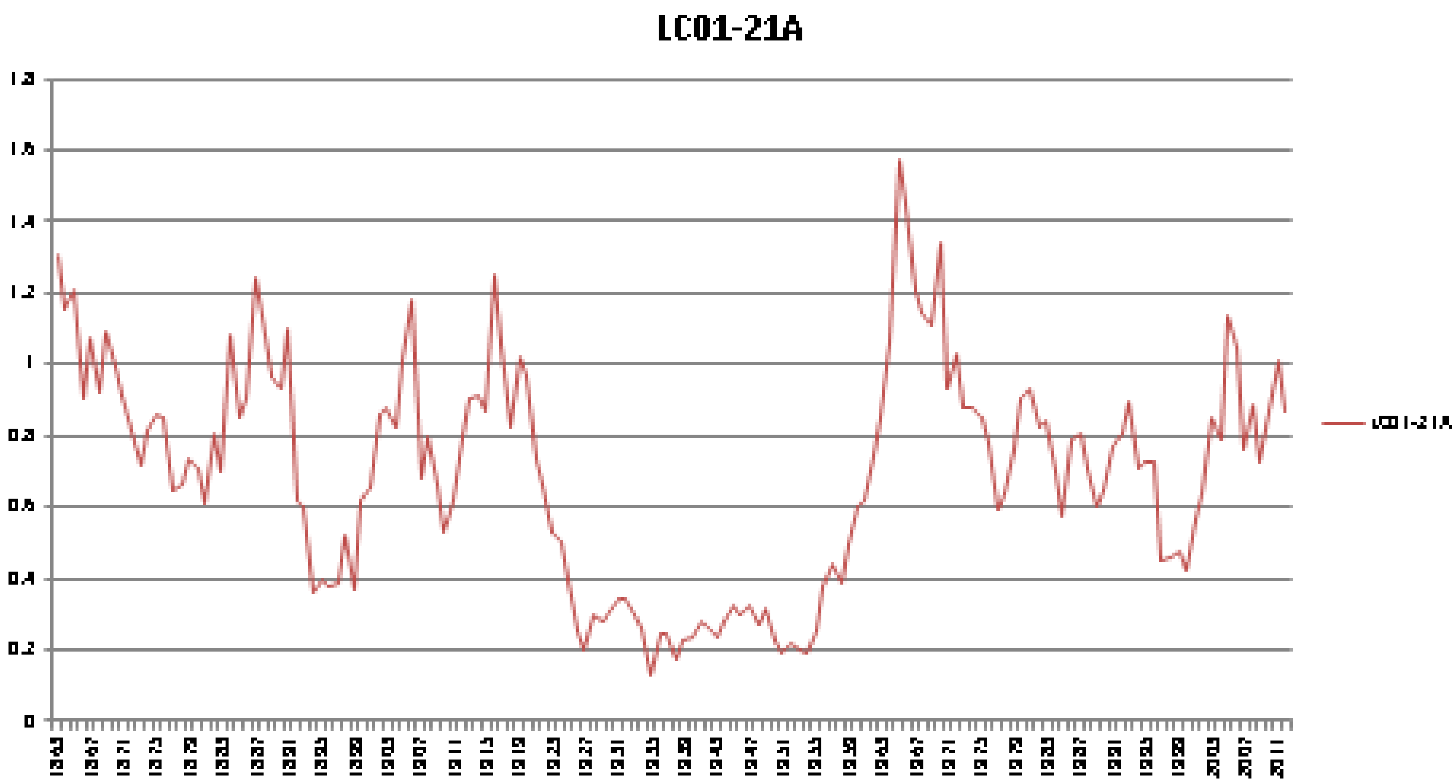
3.5
3
2.5
2
1.5
1
0.5
0
LC01-19D


LC01-21A
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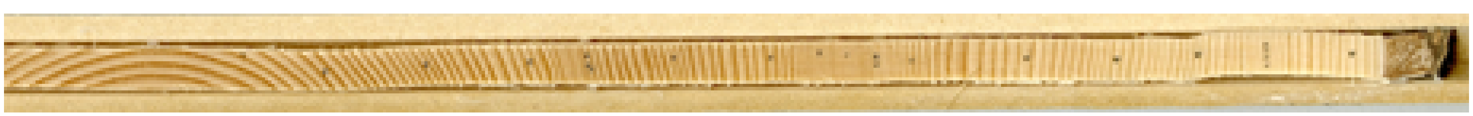
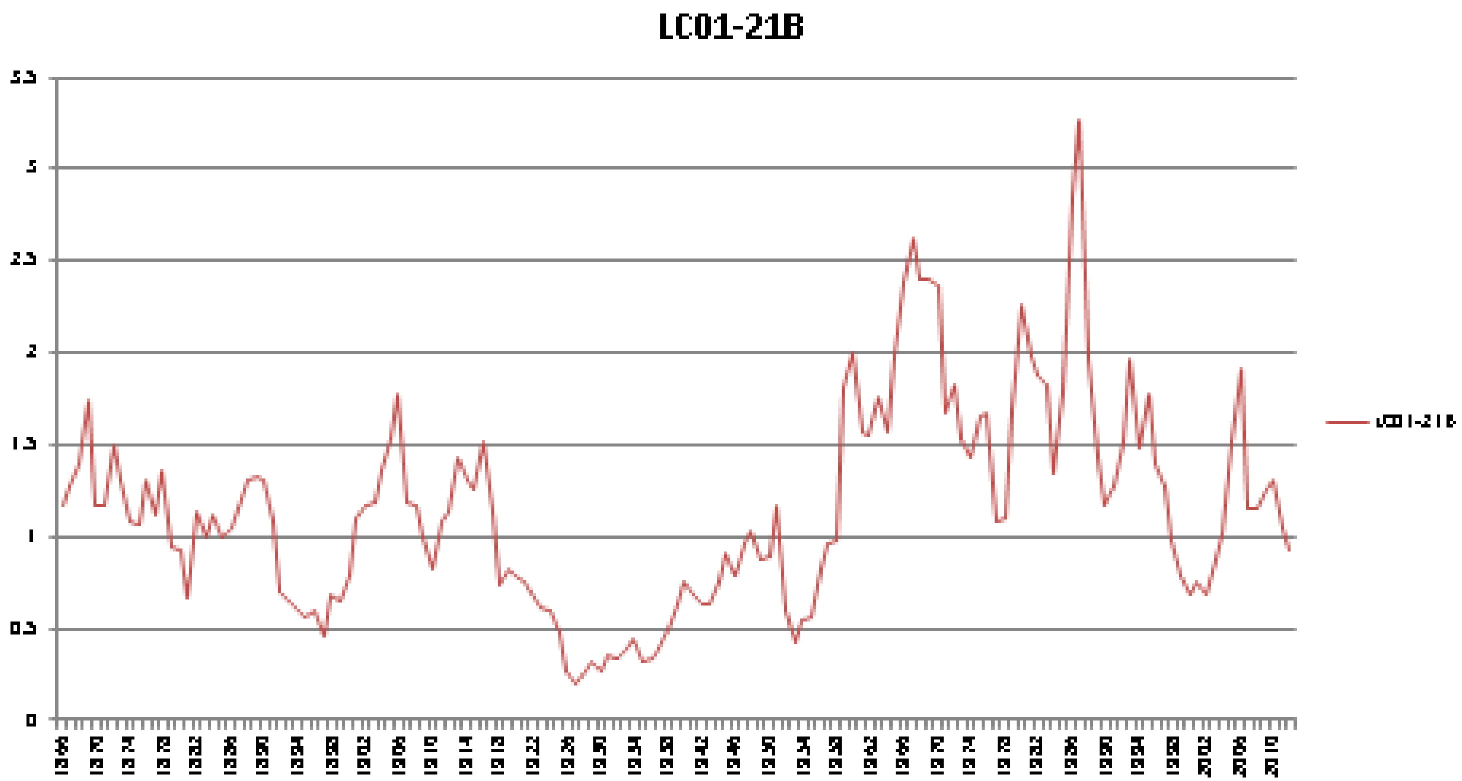
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
LC01-21A

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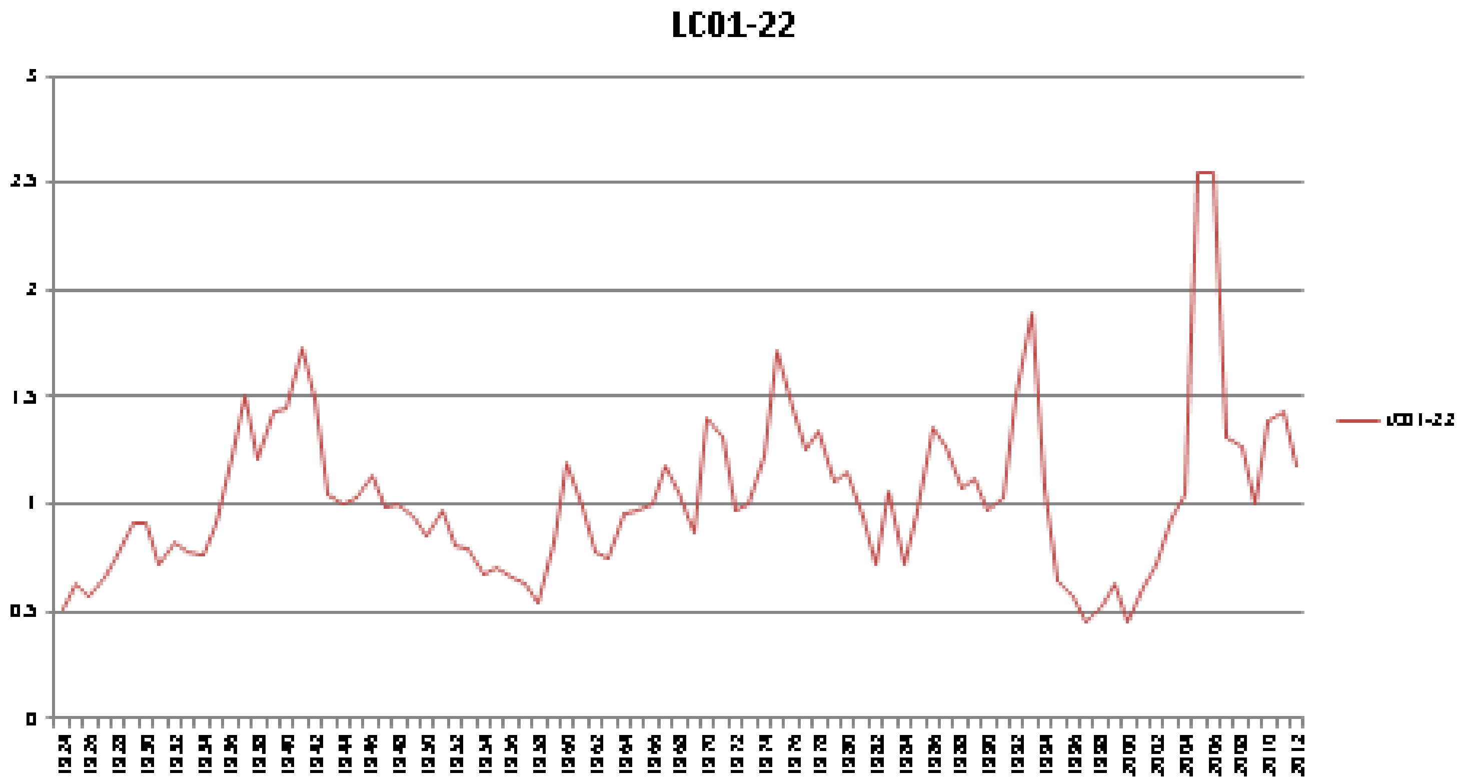
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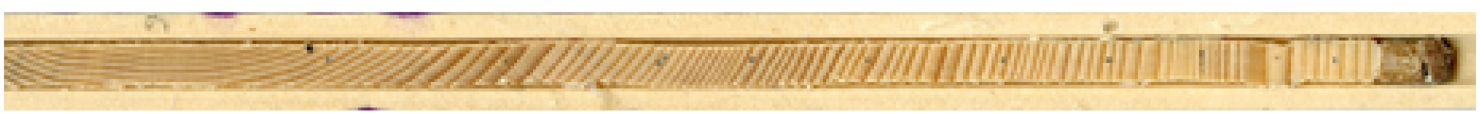
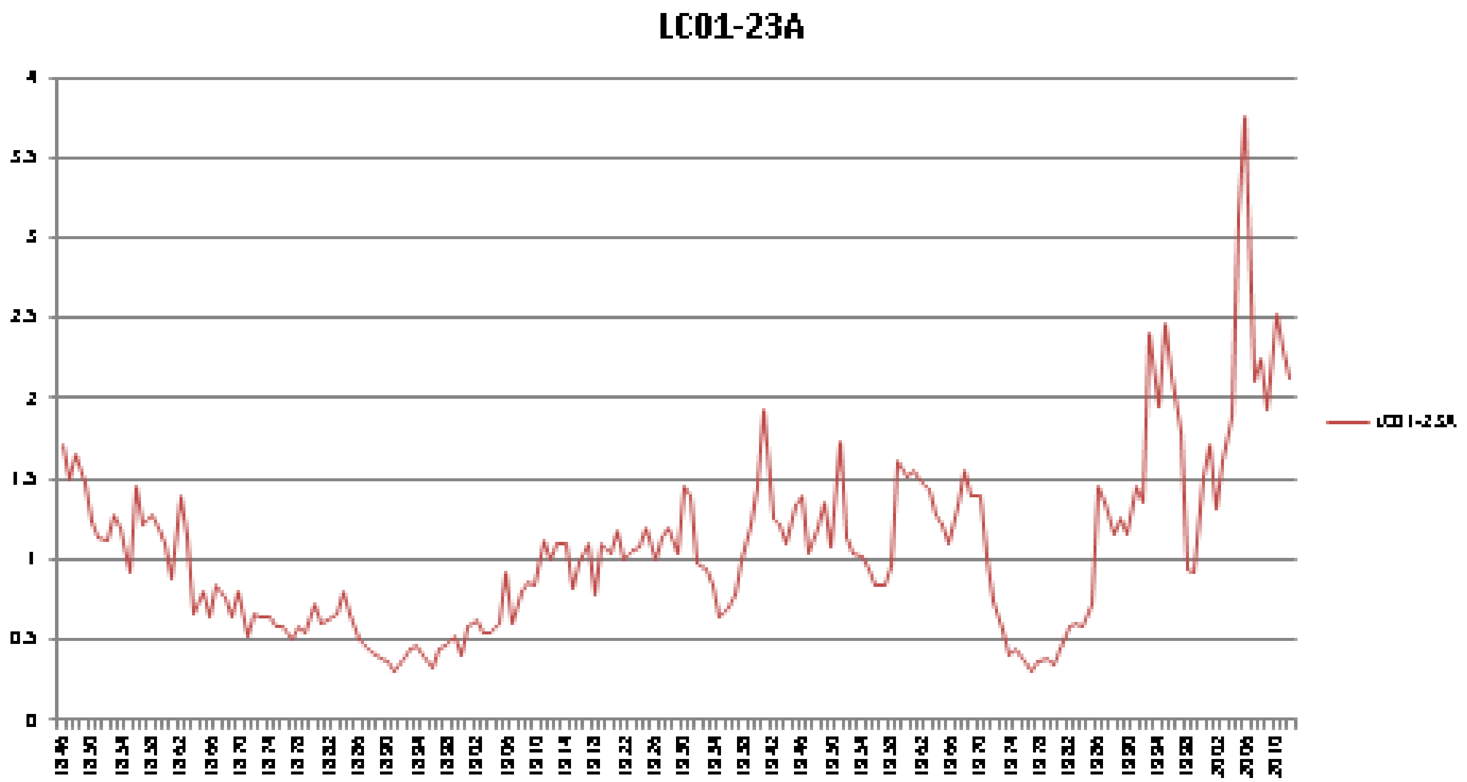
LC01-22

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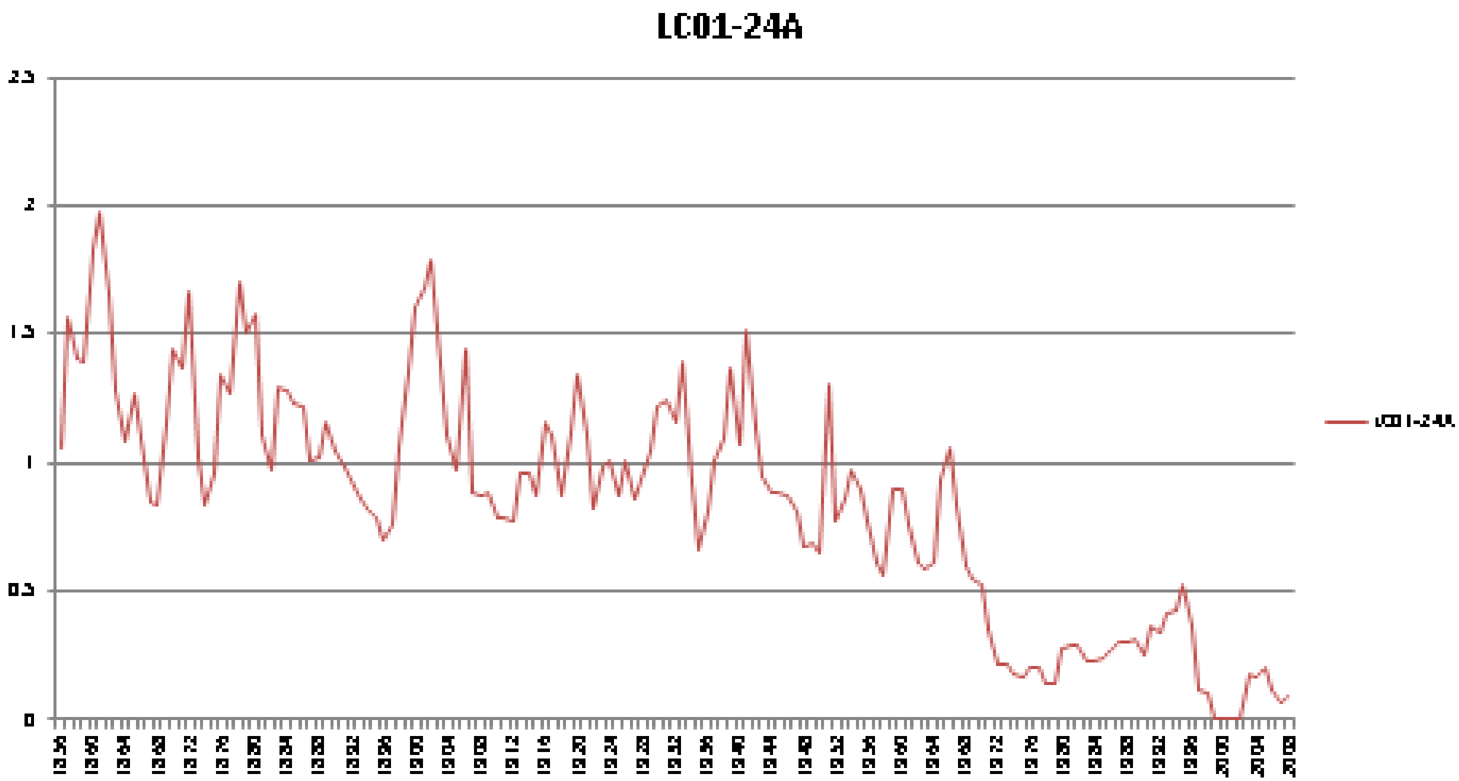
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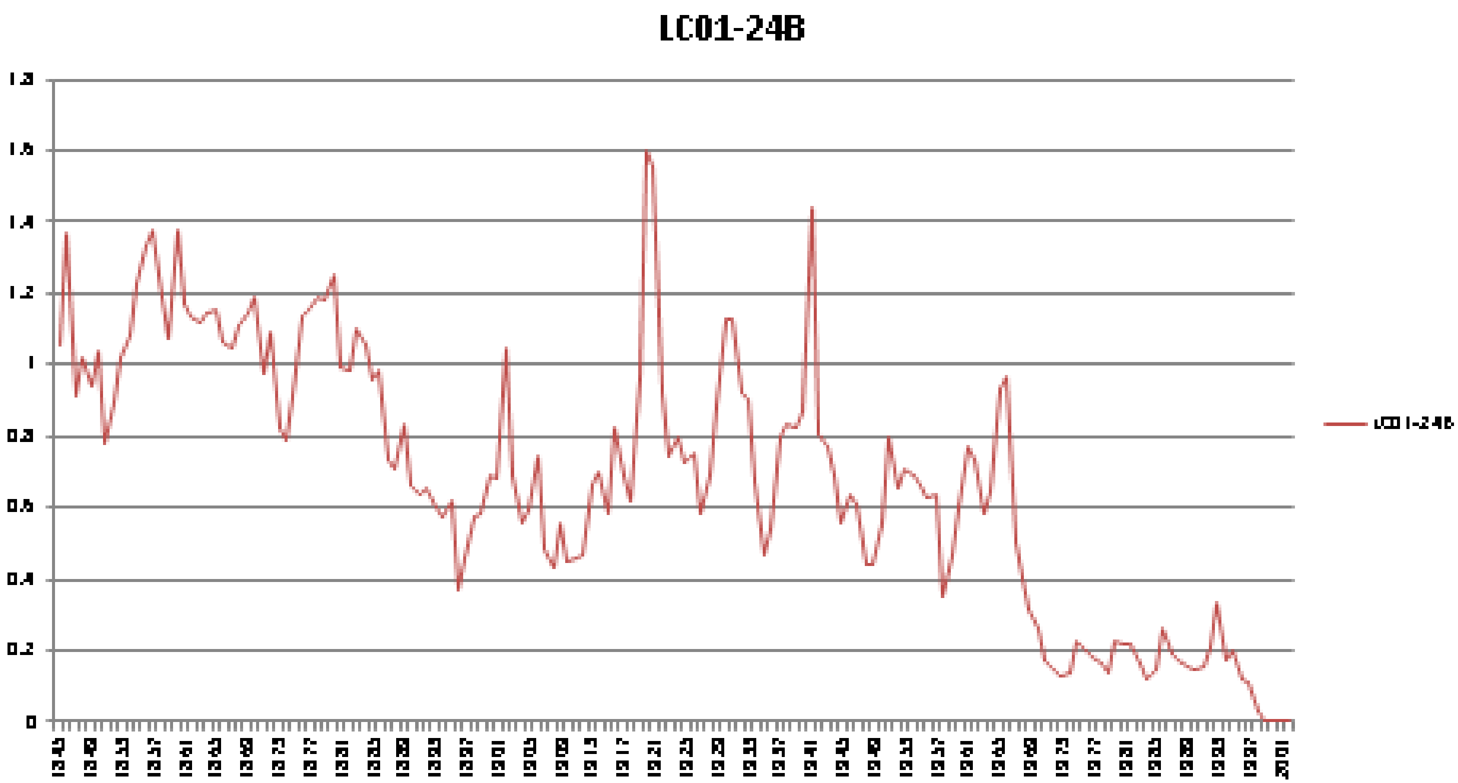
0.5
0
LC01-24A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1.4
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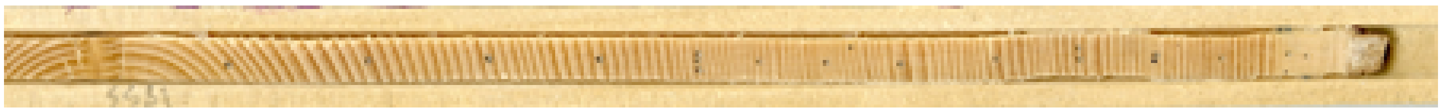
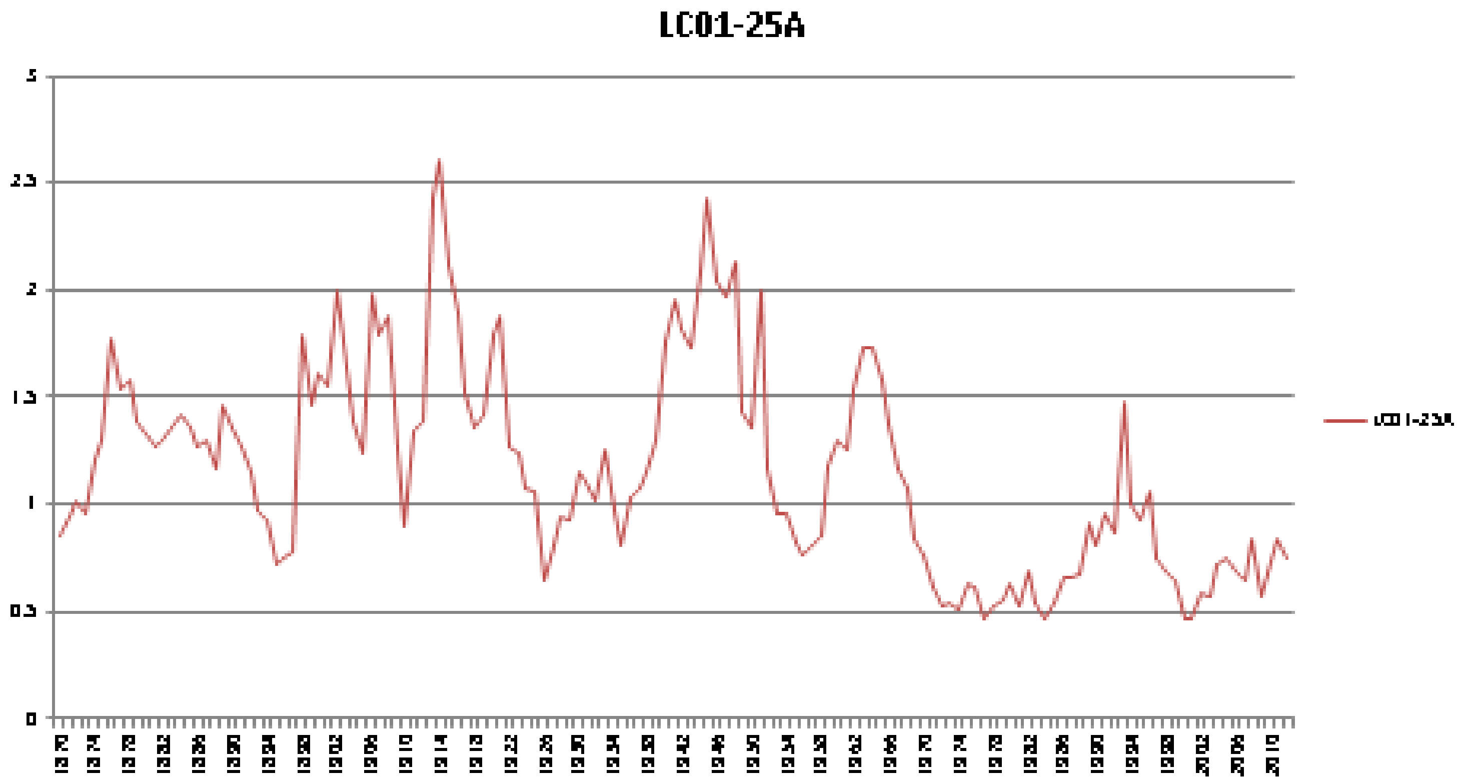
0.8
0.6
0.4
0.2
0
LC01-24B

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0.5
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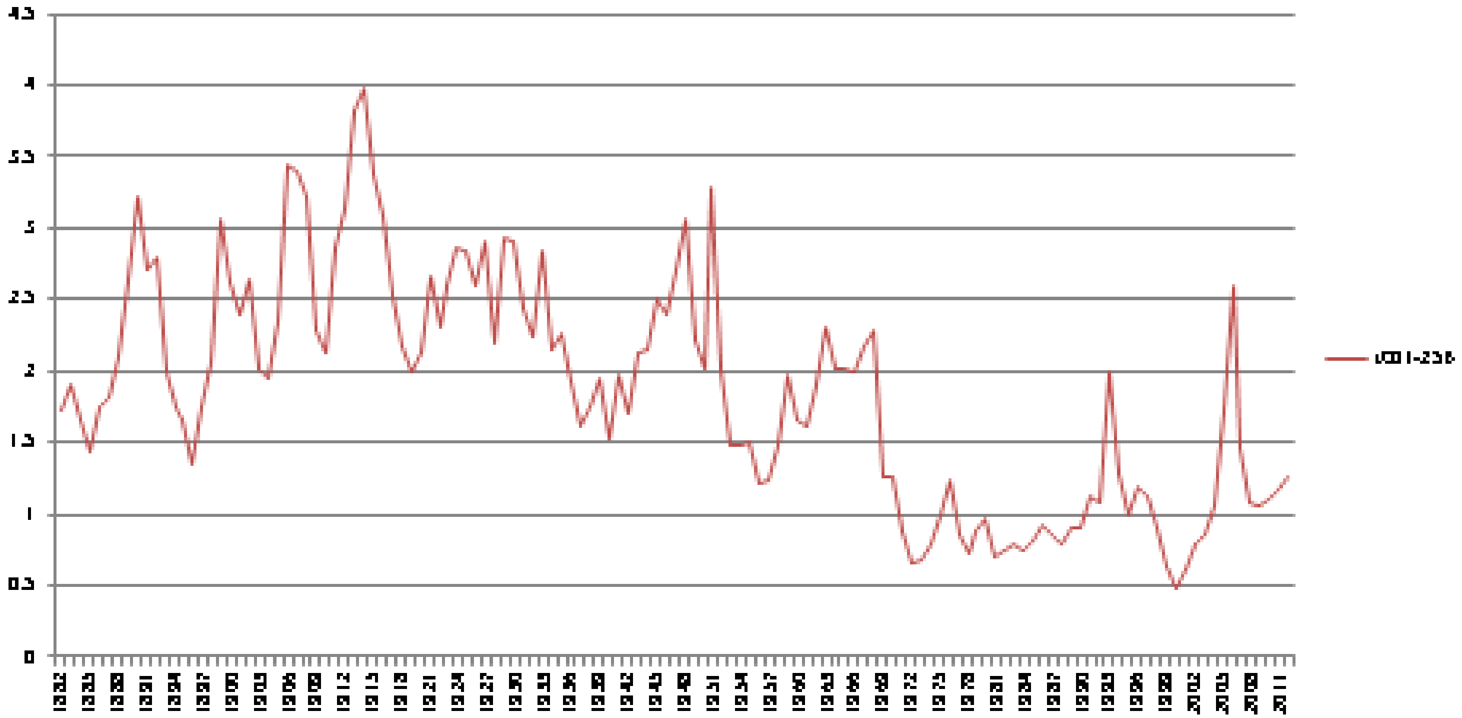
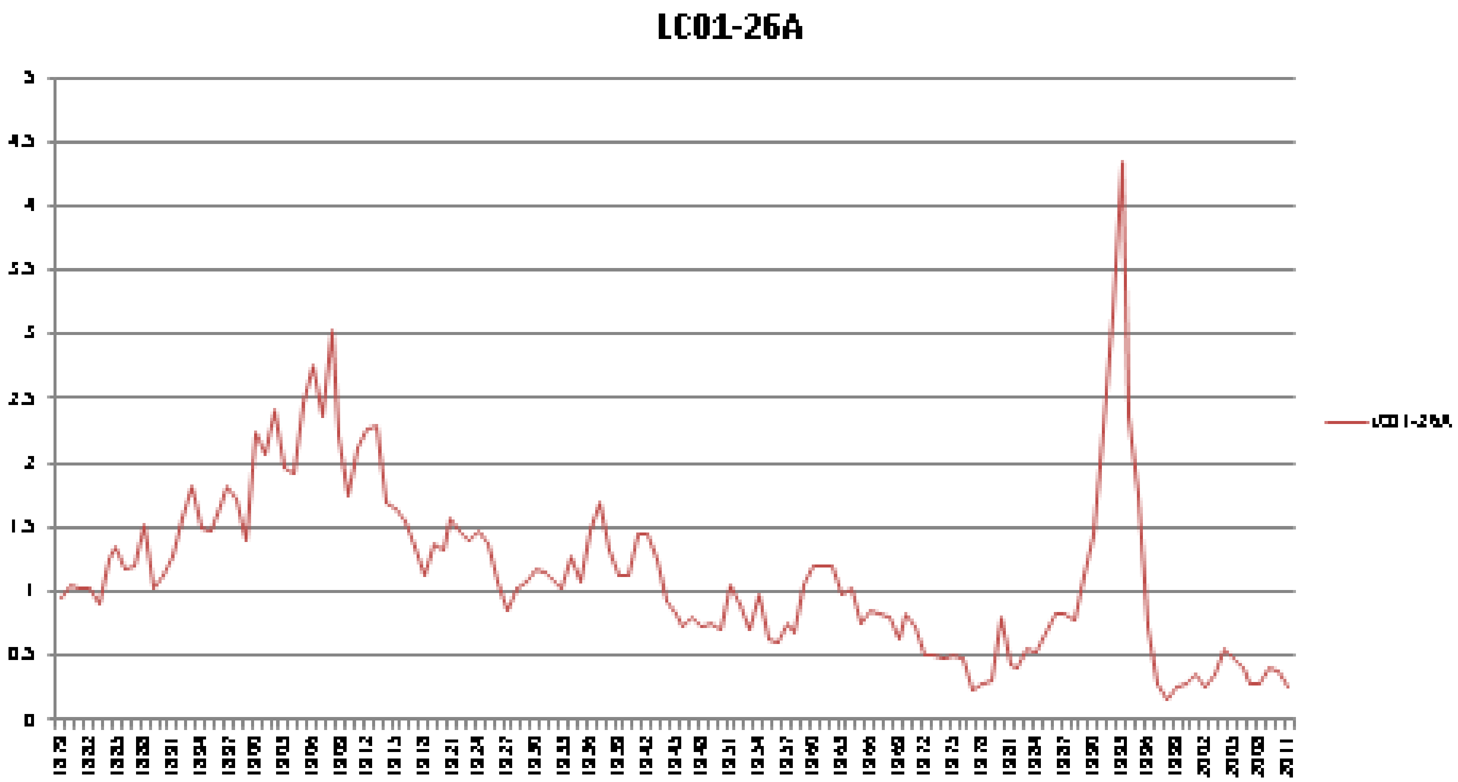
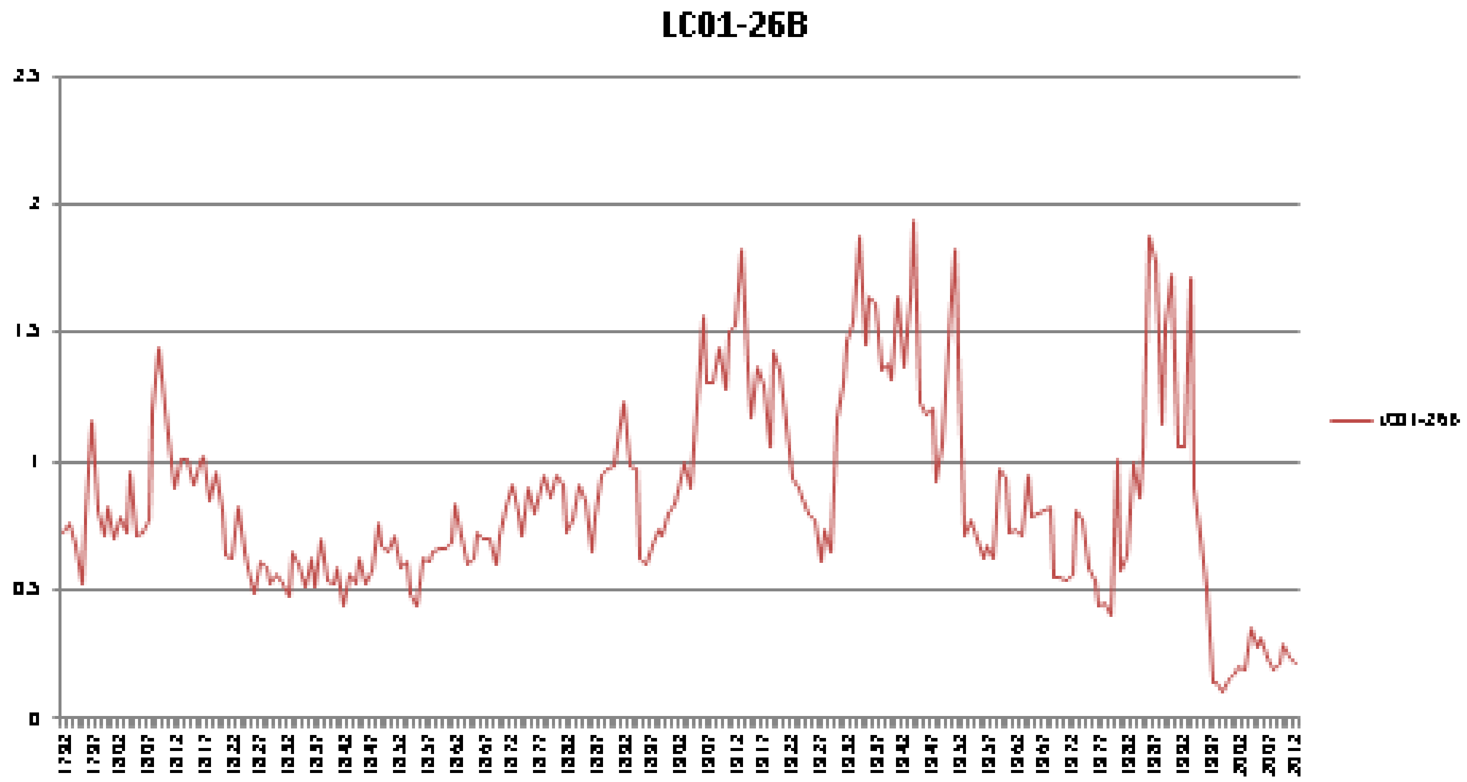
LC01-25A

LC01-25B





LC01-26A
LC01-26A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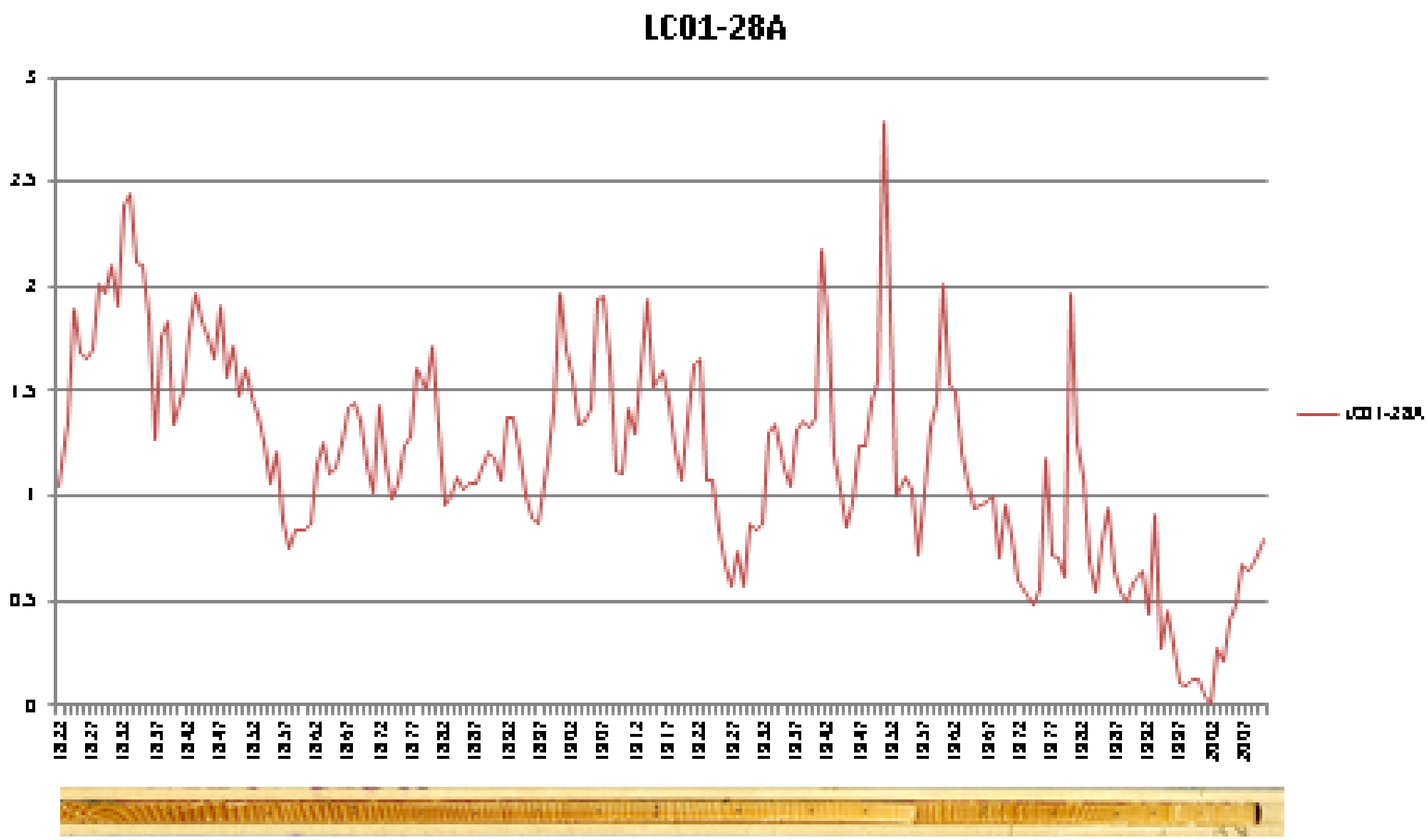
LC01-26B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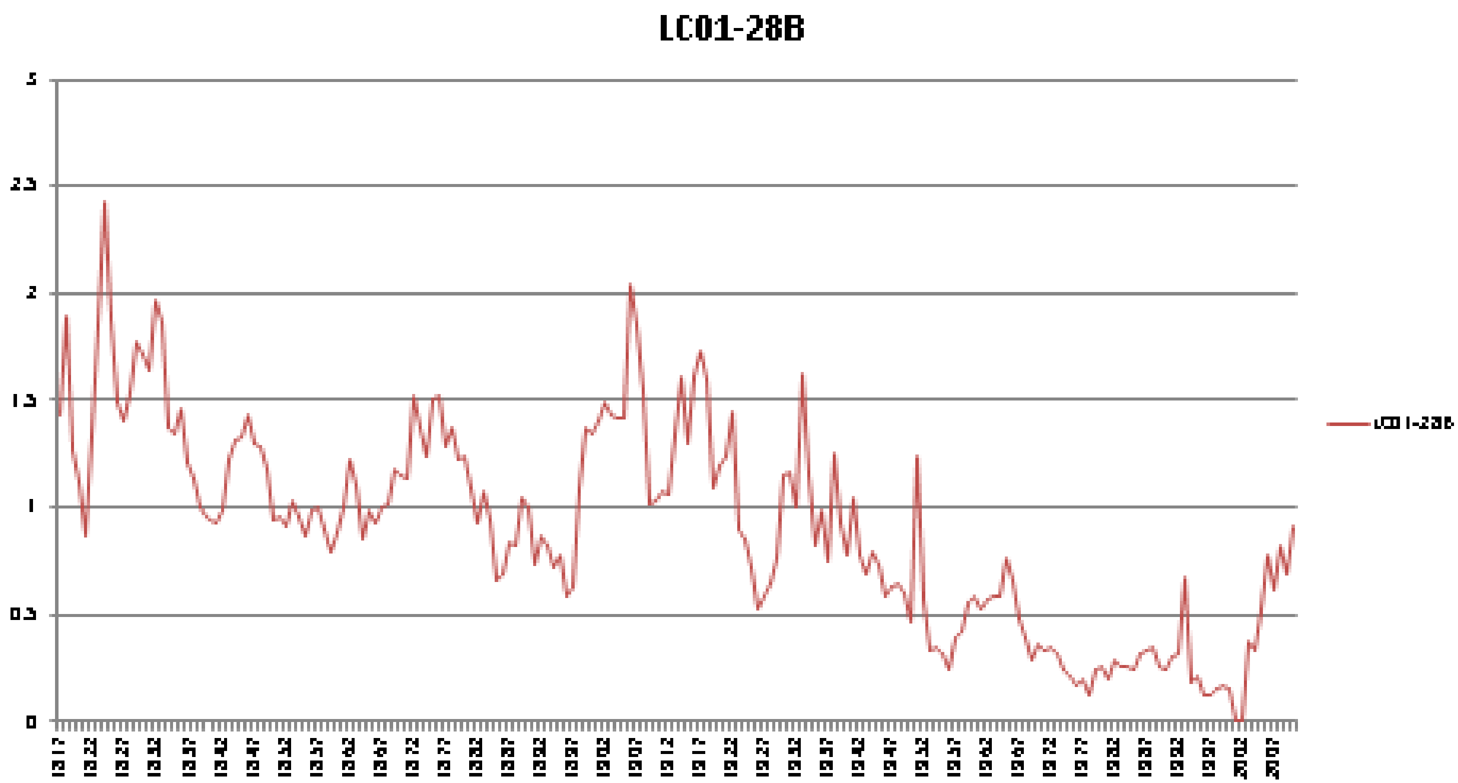
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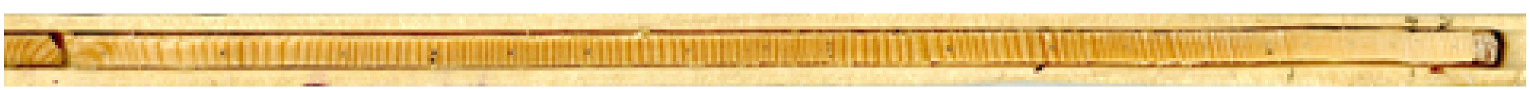
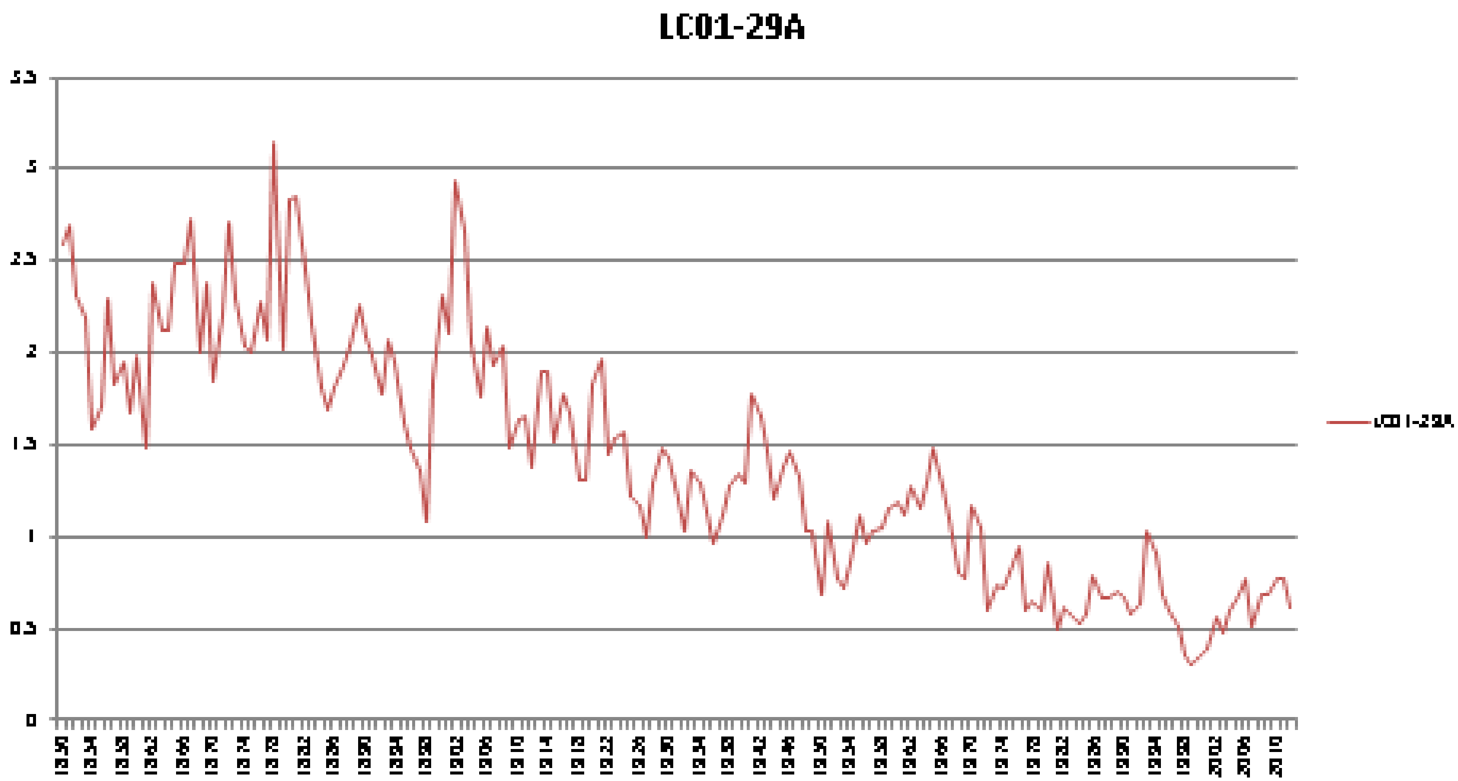
1.5
1
0.5
0
LC01-28B

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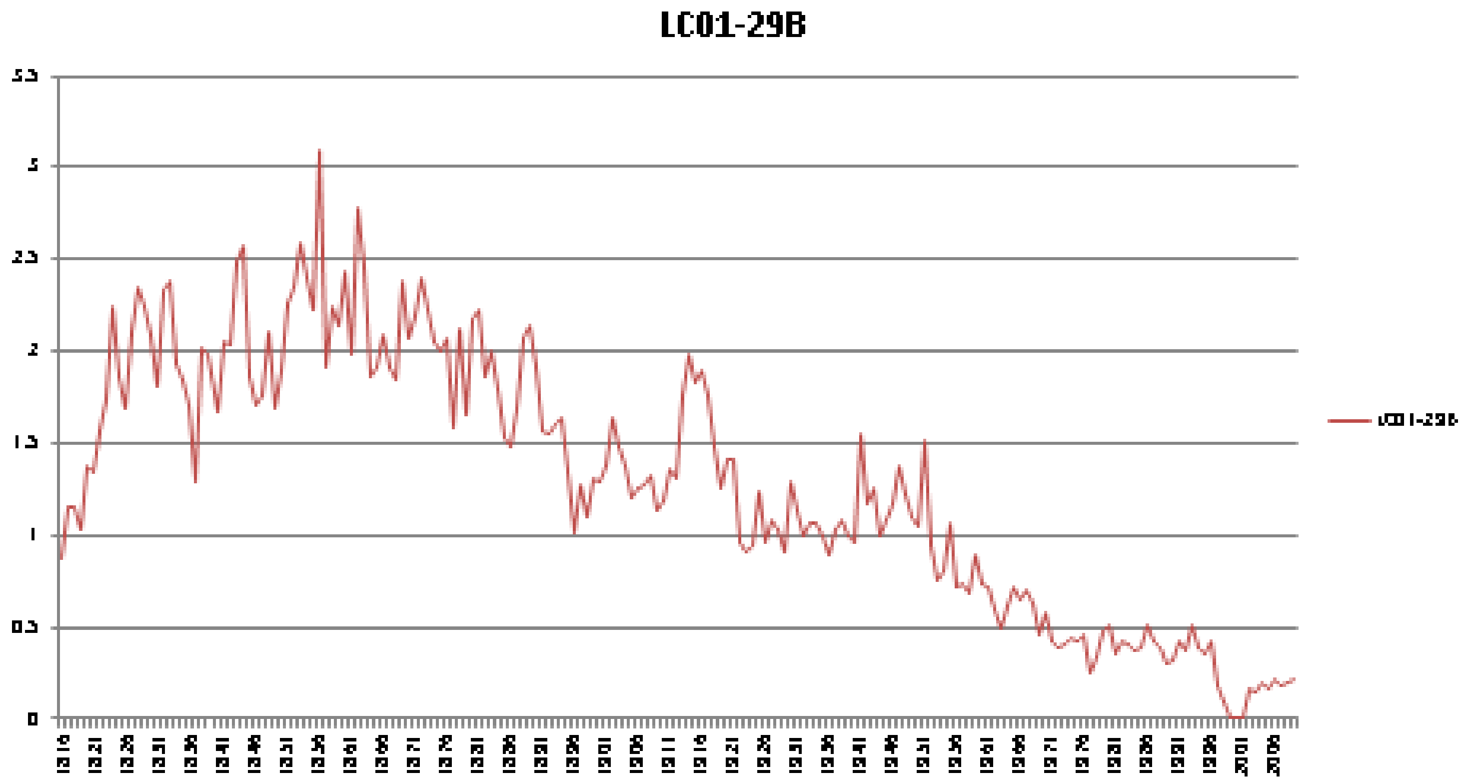
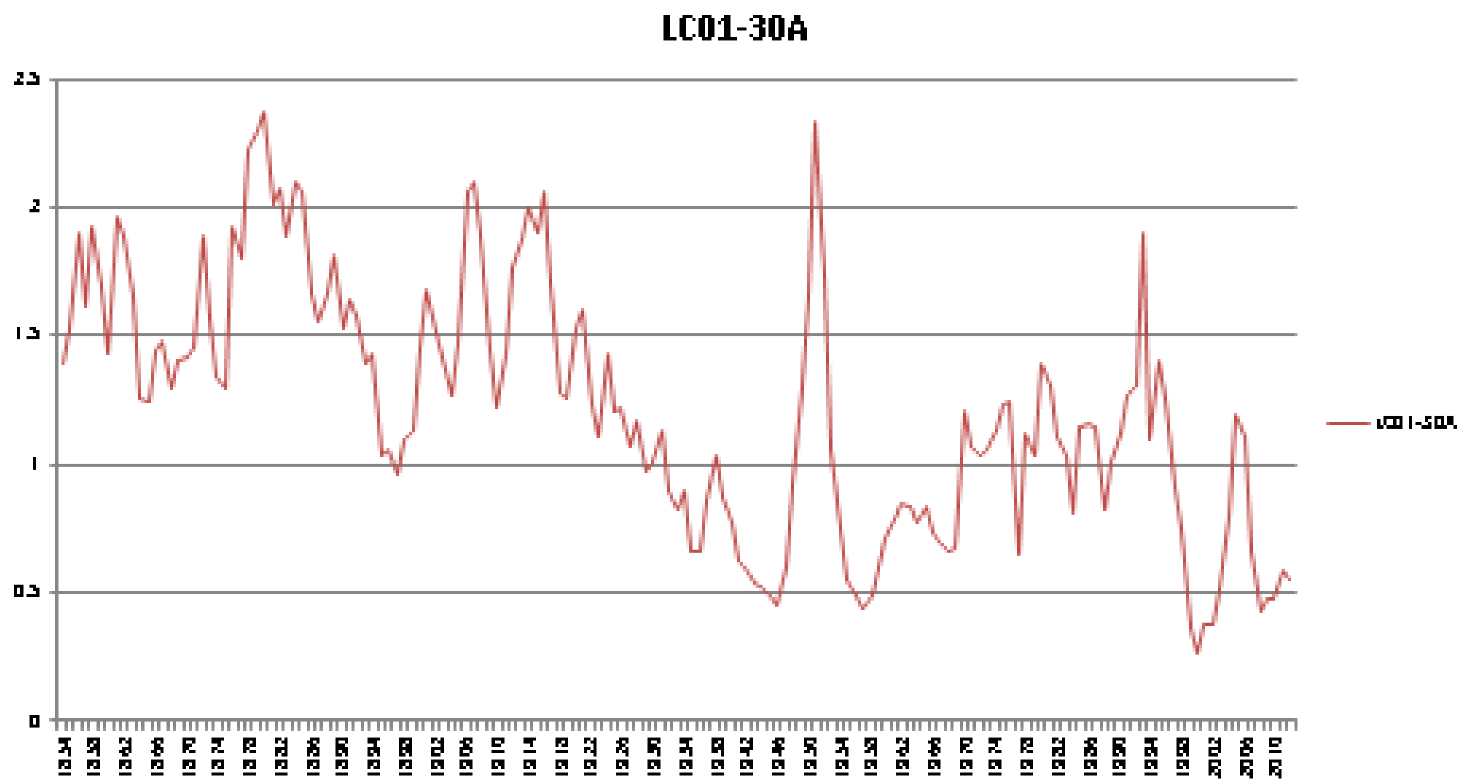
LC01-29A


LC01-29B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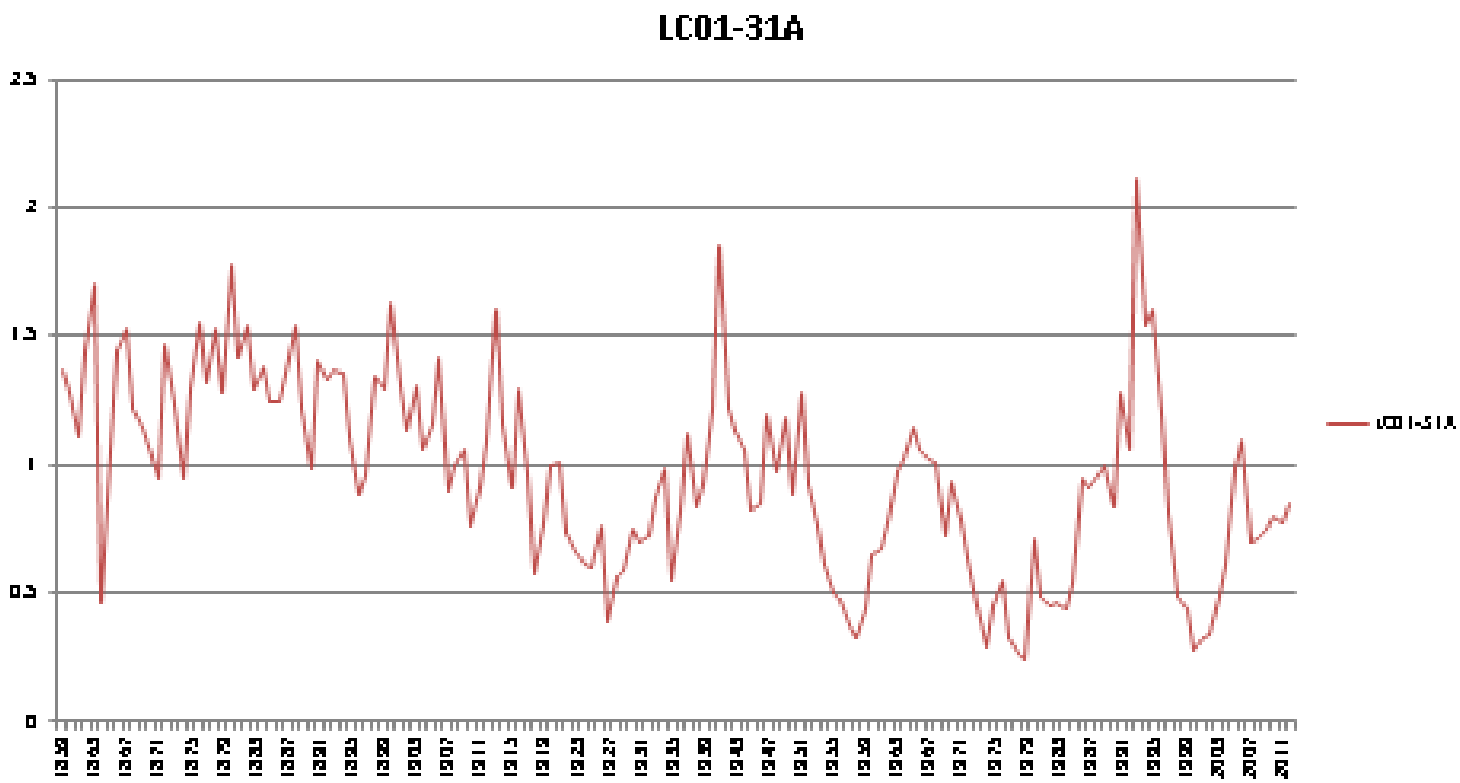
LC01-30A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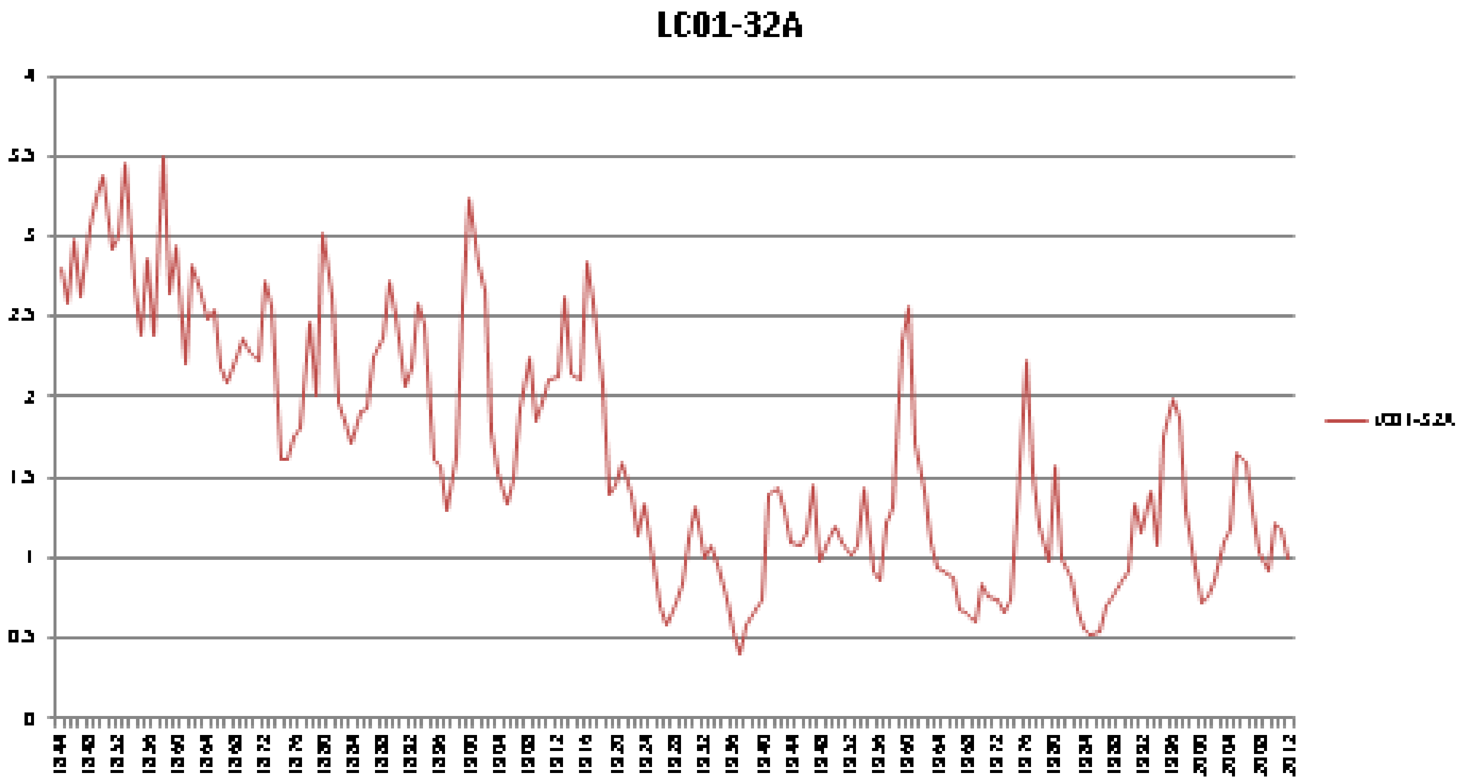
LC01-31A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3
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2
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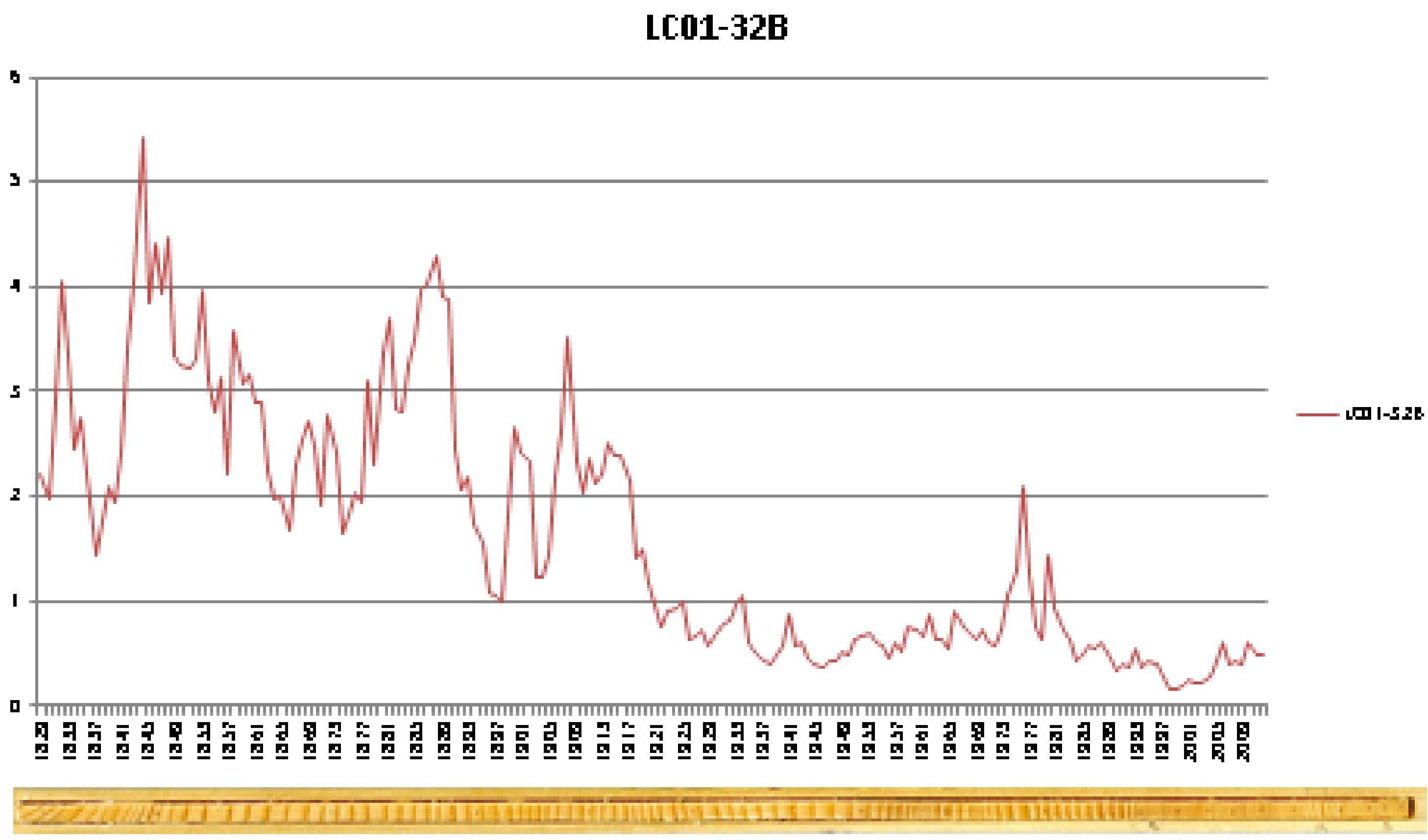
0.5
0
LC01-32A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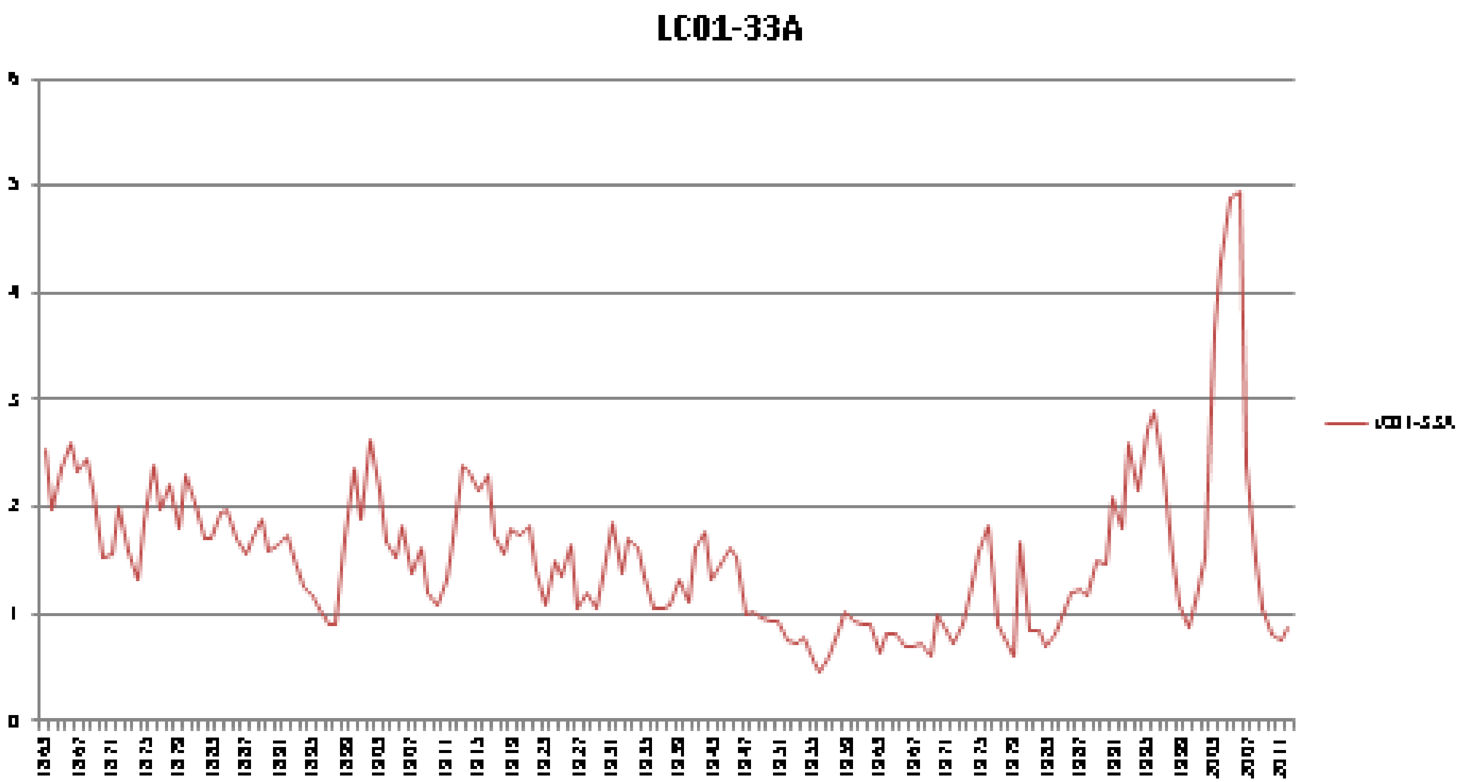
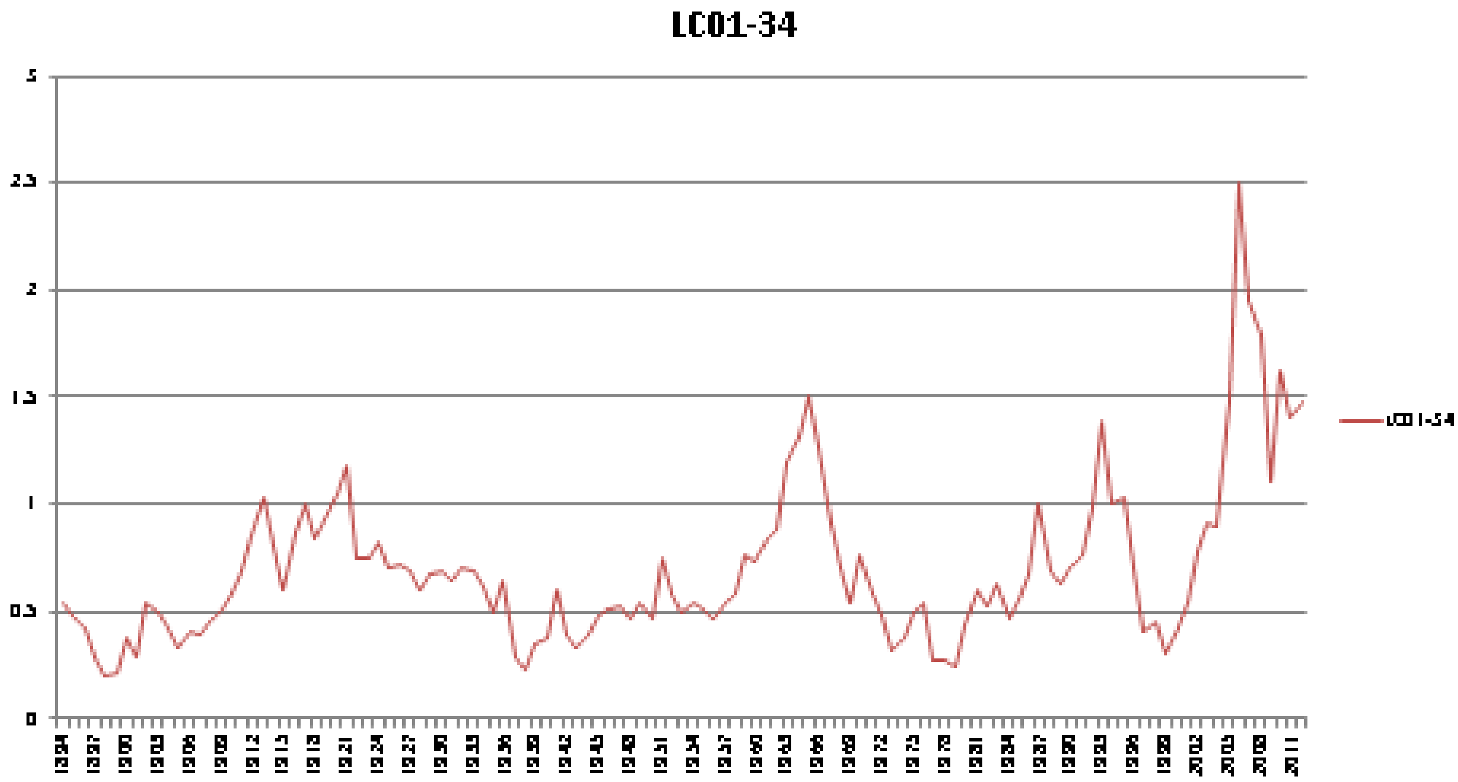


LC01-33A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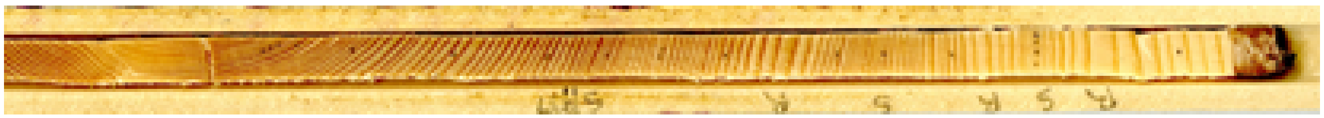
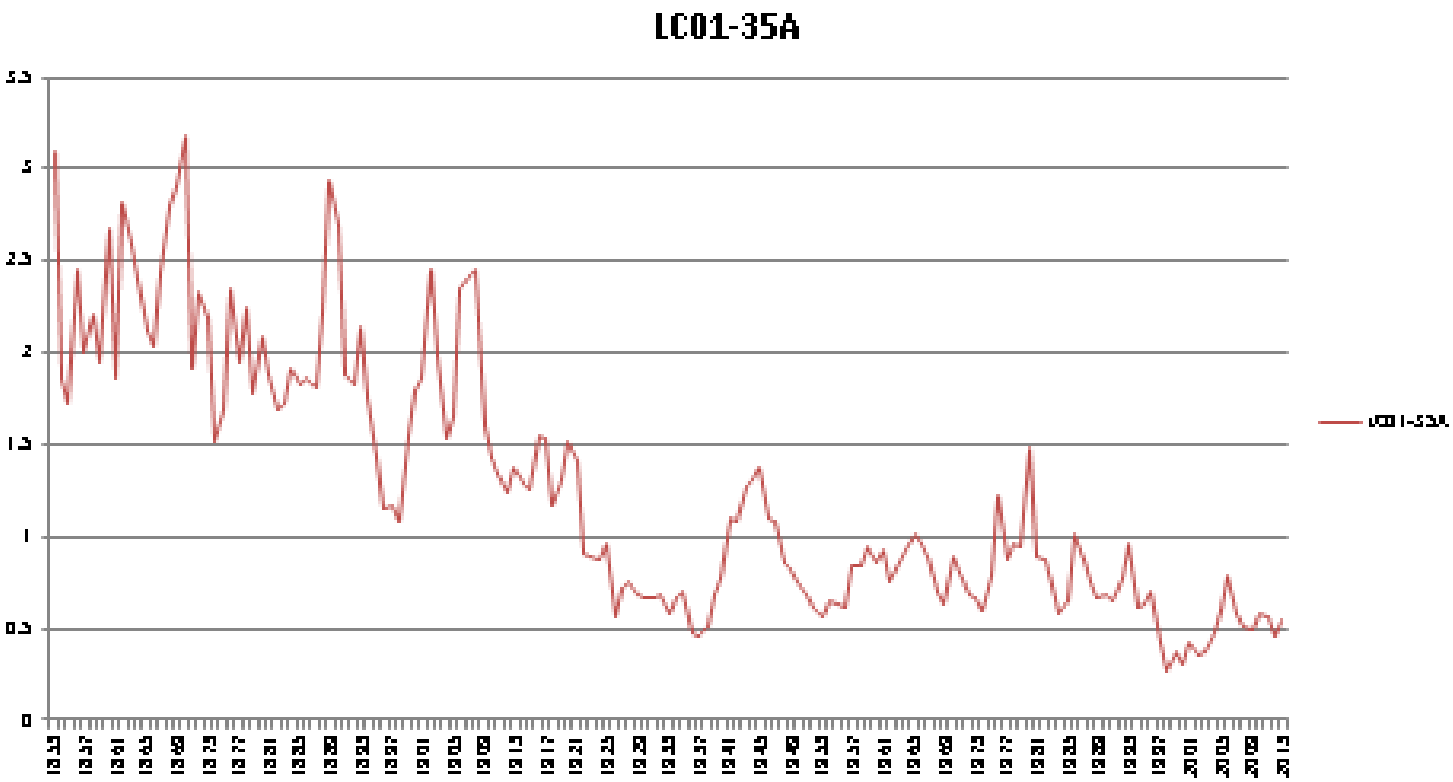
0.5
0
LC01-34

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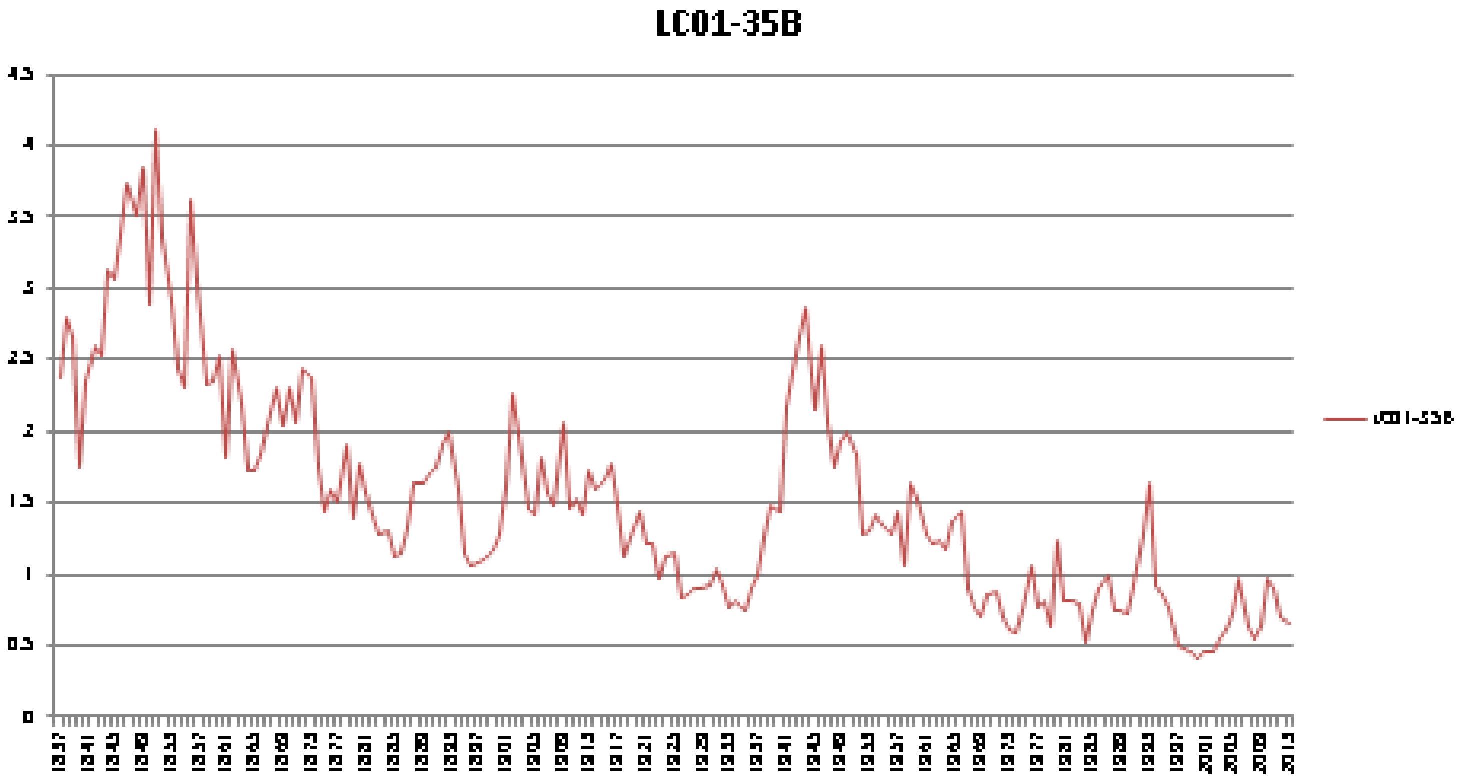
1.5
1
0.5
0
LC01-35A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2.5
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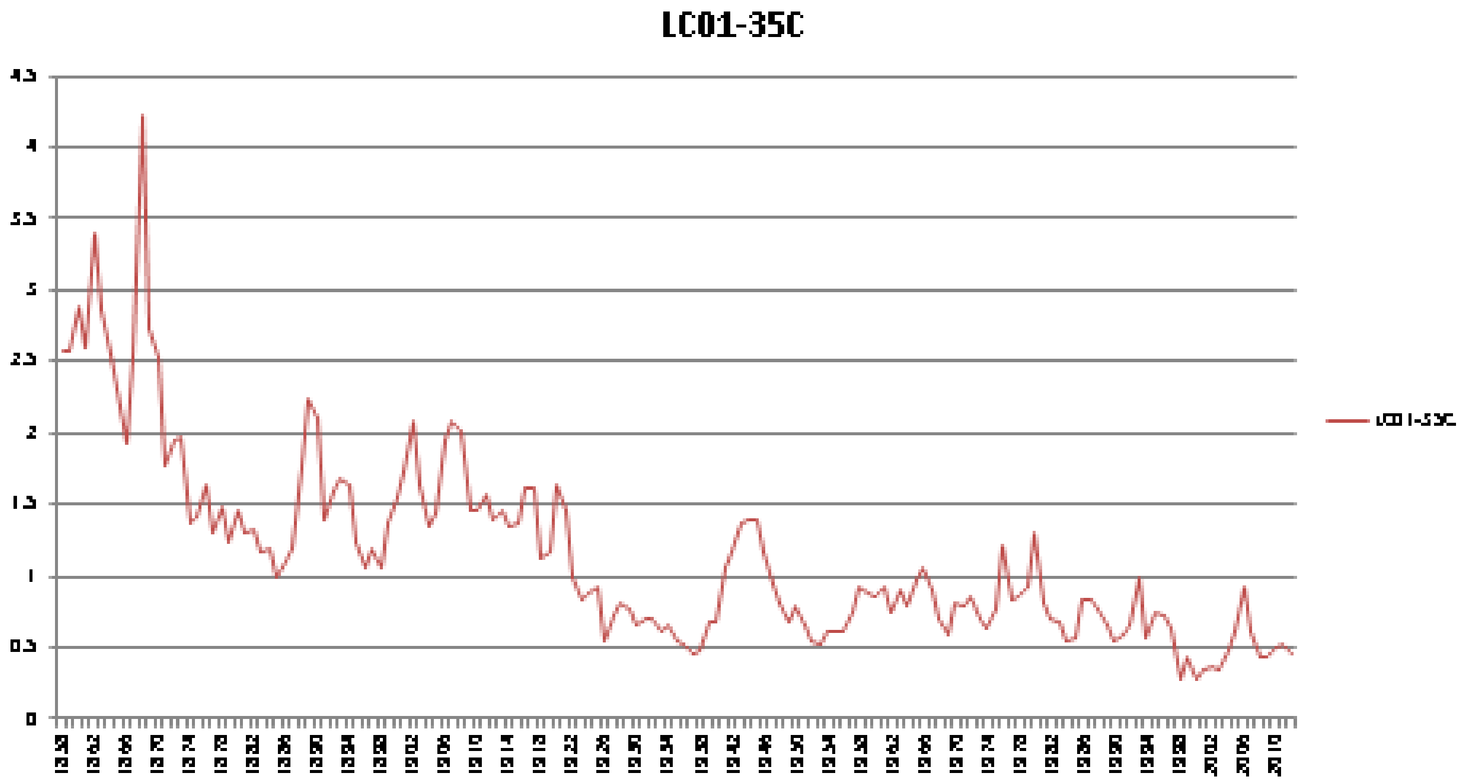
1.5
1
0.5
0
LC01-35B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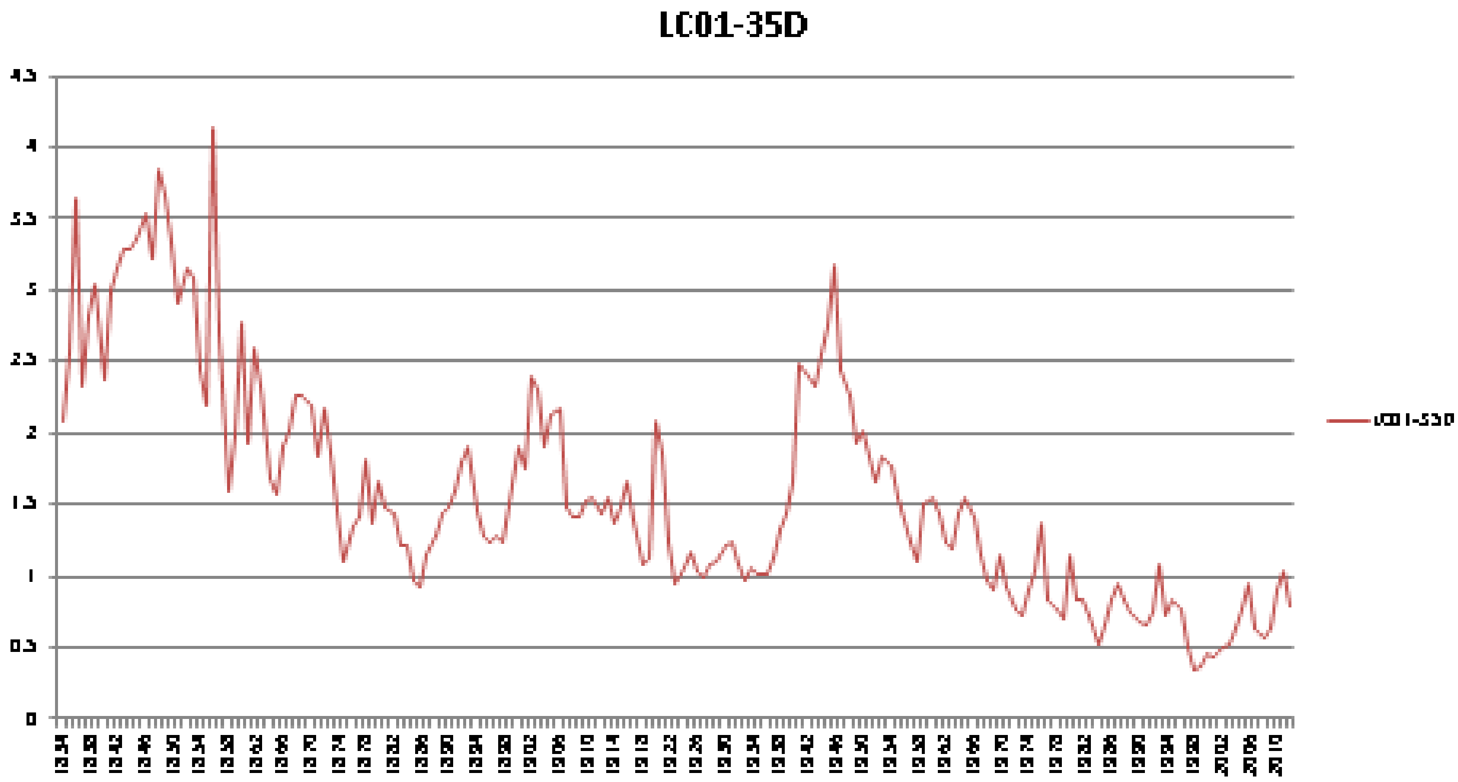
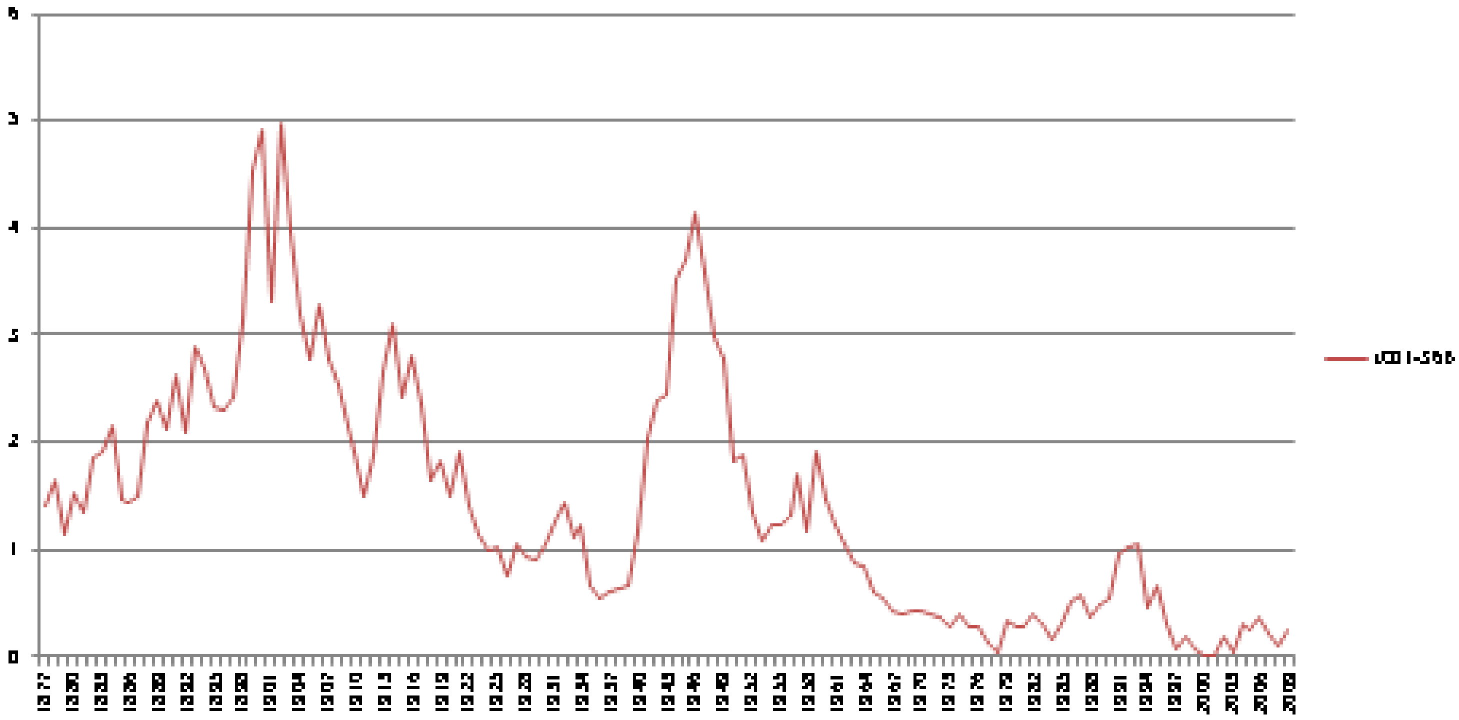
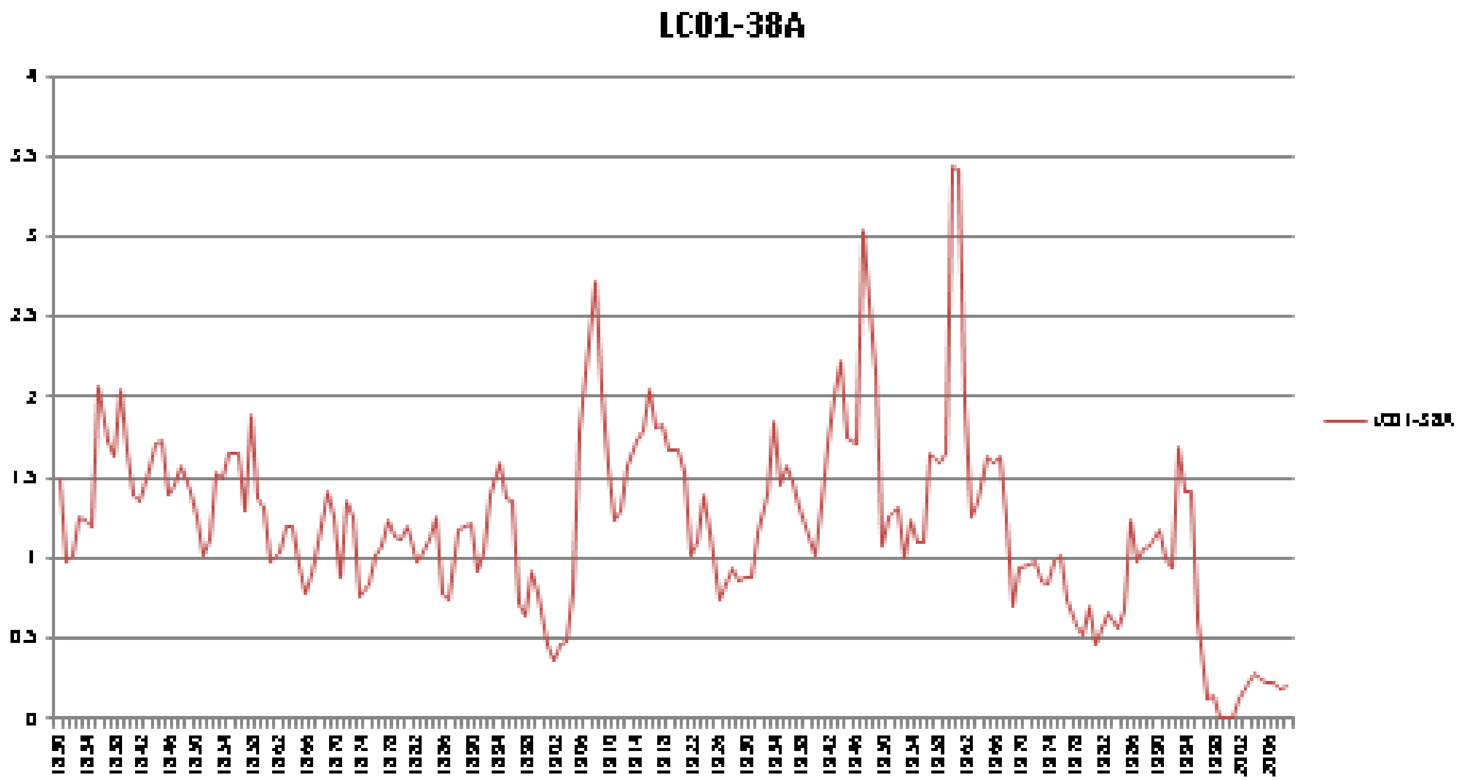
3.5
3
2.5
2
1.5
1
0.5
0
LC01-35C


LC01-35D

LC01-36B




LC01-38A
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2.5
2
1.5
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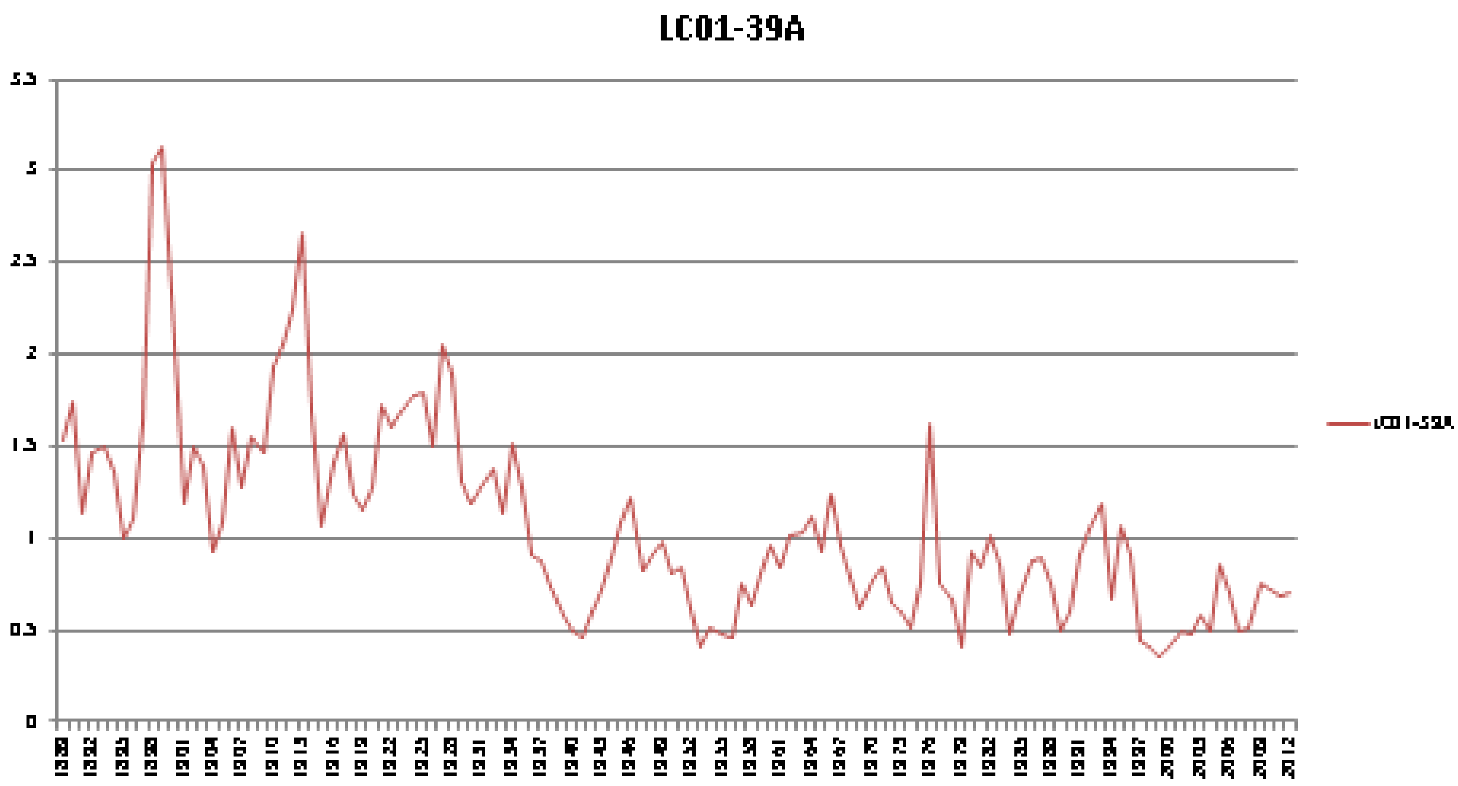
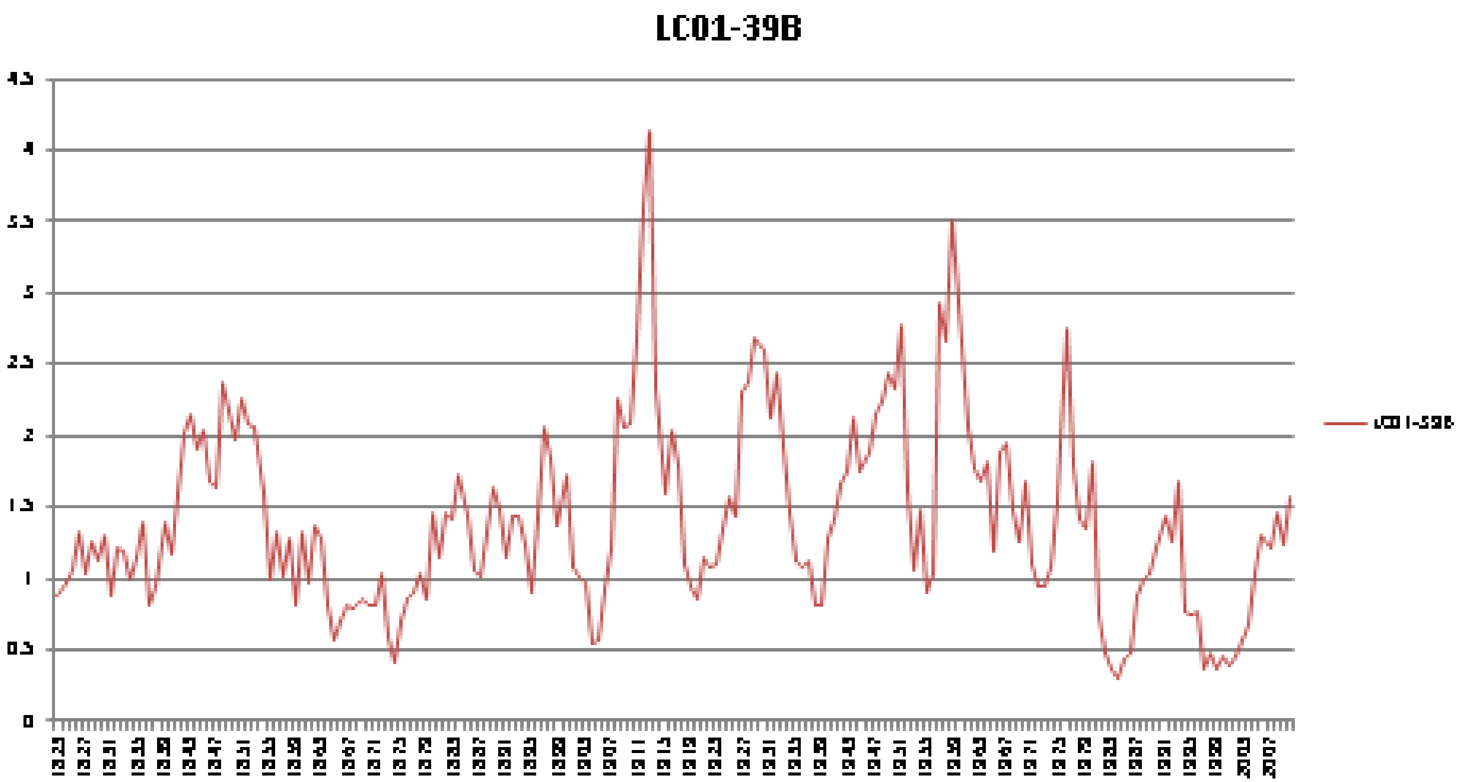
0.5
0
LC01-38A


LC01-39A
LC01-39A


LC01-39B
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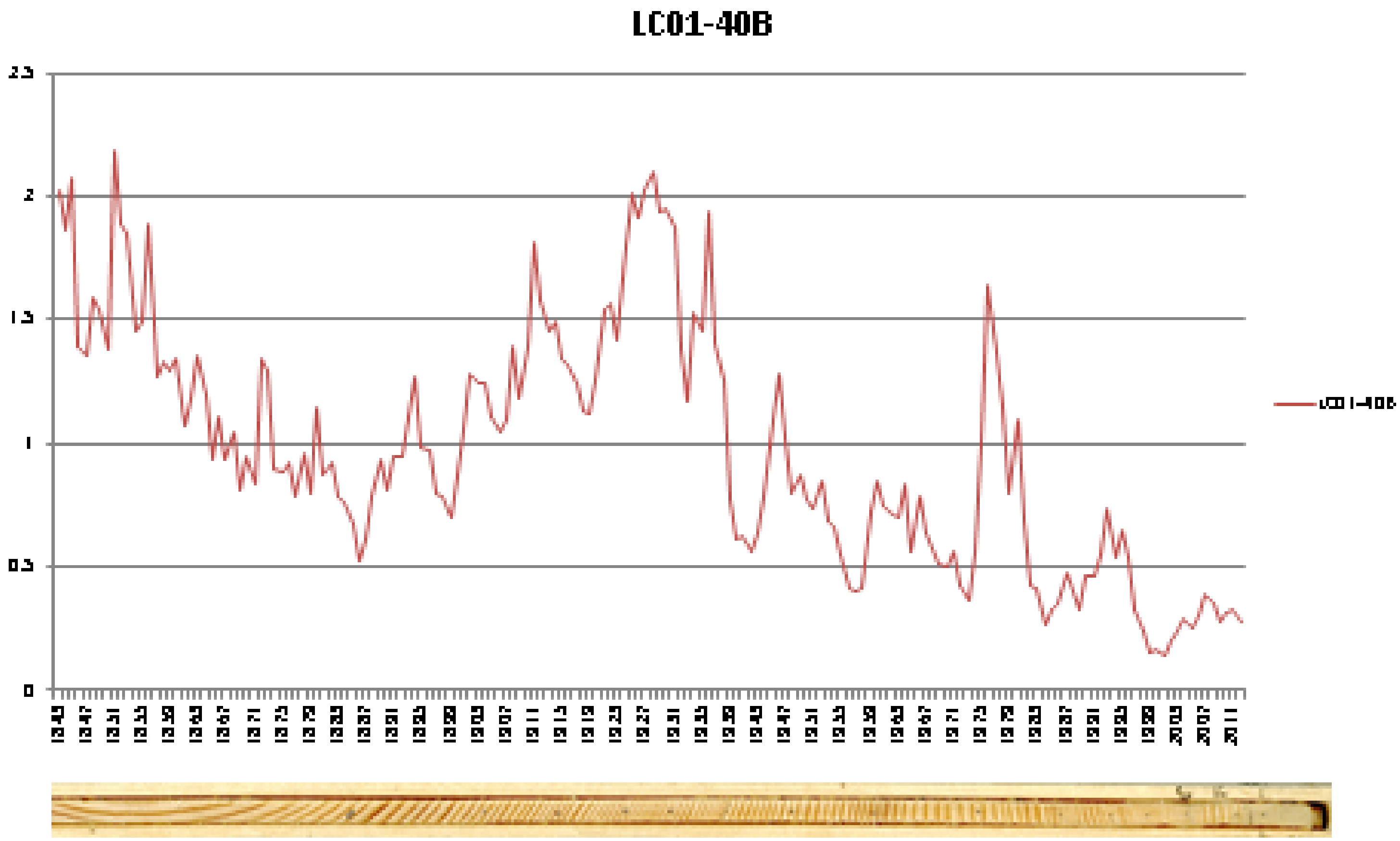
3
2.5
2
1.5
1
0.5
0
LC01-39B


LC01-40B
2.5
2
1.5
1
0.5
0

Appendix 2. Visual Analysis Spreadsheet

Visual Analysis Results			
Year	Suppression Count	Release Count	Percent Trees
1852	1		2.94
1855	1		2.94
1864	2		5.88
1866	1		2.94
1873	1		2.94
1883	1		2.94
1889		1	2.94
1890		1	2.94
1891	2		5.88
1893	4		11.76
1894	2		5.88
1895	1	1	5.88
1897	1		2.94
1898		2	5.88
1900		1	2.94
1901	1		2.94
1905		1	2.94
1907		1	2.94
1913	1		2.94
1915	1		2.94
1916	2		5.88
1919	1		2.94
1922	7		20.59
1923	2		5.88
1924	1		2.94
1926	2		5.88
1931		1	2.94
1933	1		2.94
1935	2		5.88
1936	1		2.94
1938	1	1	5.88
1939	1		2.94
1940	1	4	14.71
1941	1	1	5.88
1943		1	2.94
1944		5	14.71
1945		1	2.94
1946	1		2.94

1947		1	2.94
1948		1	2.94
1949		1	2.94
1952	13		38.24
1953	7		20.59
1954	1		2.94
1958		1	2.94
1959		2	5.88
1960	1	4	14.71
1962		1	2.94
1963		3	8.82
1965		1	2.94
1966		1	2.94
1967	2		5.88
1968	4	1	14.71
1969	2		5.88
1971	3		8.82
1972	1		2.94
1973	3		8.82
1974		1	2.94
1975	1	3	11.76
1977	1		2.94
1980	1	2	8.82
1981	3		8.82
1982	1		2.94
1983	2		5.88
1984	2		5.88
1986		3	8.82
1987		3	8.82
1989		1	2.94
1990		1	2.94
1991		2	5.88
1992		1	2.94
1993	1	2	8.82
1994	1		2.94
1995	1	1	5.88
1996	3	1	11.76
1997	11		32.35
1998	9		26.47
1999	1		2.94
2004		1	2.94
2005		4	11.76

Appendix 3. COFECHA output for final LC01 chronology

```
[]  Dendrochronology Program Library                                        Run TEST   Program COF  11:05  Fri 30 Apr 2010  Page   1
[]
[]  P R O G R A M      C O F E C H A                                                                          Version 6.06P    27515
------------------------------------------------------------------------------------------------------------------------------------

 QUALITY CONTROL AND DATING CHECK OF TREE-RING MEASUREMENTS

 File of DATED series:   good.txt

 CONTENTS:

    Part 1:  Title page, options selected, summary, absent rings by series
    Part 2:  Histogram of time spans
    Part 3:  Master series with sample depth and absent rings by year
    Part 4:  Bar plot of Master Dating Series
    Part 5:  Correlation by segment of each series with Master
    Part 6:  Potential problems: low correlation, divergent year-to-year changes, absent rings, outliers
    Part 7:  Descriptive statistics

 RUN CONTROL OPTIONS SELECTED                             VALUE

        1  Cubic smoothing spline 50% wavelength cutoff for filtering
                                                            32 years
        2  Segments examined are                            40 years lagged successively by  20 years
        3  Autoregressive model applied                      A  Residuals are used in master dating series and testing
        4  Series transformed to logarithms                  Y  Each series log-transformed for master dating series and testing
        5  CORRELATION is Pearson (parametric, quantitative)
           Critical correlation, 99% confidence level   .3665
        6  Master dating series saved                        N
        7  Ring measurements listed                          N
        8  Parts printed                               1234567
        9  Absent rings are omitted from master series and segment correlations  (Y)

 Time span of Master dating series is  1792 to  2013   222 years
 Continuous time span is               1792 to  2013   222 years
 Portion with two or more series is    1815 to  2013   199 years


                                       ****************************************
                                       *C* Number of dated series       59 *C*
                                       *O* Master series 1792 2013  222 yrs *O*
                                       *F* Total rings in all series   8827 *F*
                                       *E* Total dated rings checked   8804 *E*
                                       *C* Series intercorrelation     .534 *C*
                                       *H* Average mean sensitivity    .204 *H*
                                       *A* Segments, possible problems   50 *A*
                                       *** Mean length of series      149.6 ***
                                       ****************************************
```

```
ABSENT RINGS listed by SERIES:            (See Master Dating Series for absent rings listed by year)

LC01-3D     1 absent rings:   1999
LC01-8A     7 absent rings:   1984  1998  1999  2000  2001  2002  2003
LC01-14     2 absent rings:   1999  2000
LC01-18A    1 absent rings:   1984
LC01-18B    1 absent rings:   1984
LC01-19D    1 absent rings:   1978
LC01-24A    4 absent rings:   1999  2000  2001  2002
LC01-24B    5 absent rings:   1999  2000  2001  2002  2003
LC01-28A    1 absent rings:   2002
LC01-28B    2 absent rings:   2001  2002
LC01-29B    3 absent rings:   1999  2000  2001
LC01-36B    2 absent rings:   2000  2001
LC01-38A    3 absent rings:   1999  2000  2001

           33 absent rings    .374%
```

```
PART 2:  TIME PLOT OF TREE-RING SERIES:                                                       11:05  Fri 30 Apr 2010  Page   2
------------------------------------------------------------------------------------------------------------------------------------
 1050 1100 1150 1200 1250 1300 1350 1400 1450 1500 1550 1600 1650 1700 1750 1800 1850 1900 1950 2000 2050 Ident   Seq Time-span  Yrs
   :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    : -------- --- ---- ---- ----
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  <=============>   . LC01-1C    1 1881 2013  133
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .     <================>   . LC01-2D    2 1851 2013  163
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    <=================>   . LC01-2E    3 1840 2012  173
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .   <==========>   . LC01-3C    4 1905 2013  109
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . <===================>   . LC01-3D    5 1823 2013  191
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . <==============>   . LC01-4C    6 1873 2013  141
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    <=================>   . LC01-4D    7 1848 2013  166
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    <=================>   . LC01-5B    8 1843 2012  170
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .     <================>   . LC01-5C    9 1850 2013  164
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .  <=============>   . LC01-5D   10 1886 2013  128
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .<====================>   . LC01-5E   11 1819 2013  195
   .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .<====================>   . LC01-8A   12 1815 2012  198
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```

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  .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    . <===========>.    . LC01-19C  29 1873 1990  118
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 1050 1100 1150 1200 1250 1300 1350 1400 1450 1500 1550 1600 1650 1700 1750 1800 1850 1900 1950 2000 2050

PART 2:  TIME PLOT OF TREE-RING SERIES:                                                   11:05  Fri 30 Apr 2010  Page   3
------------------------------------------------------------------------------------------------------------------------------------
 1050 1100 1150 1200 1250 1300 1350 1400 1450 1500 1550 1600 1650 1700 1750 1800 1850 1900 1950 2000 2050 Ident    Seq Time-span  Yrs
  :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    : -------- --- ---- ---- ----
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  :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :    :
 1050 1100 1150 1200 1250 1300 1350 1400 1450 1500 1550 1600 1650 1700 1750 1800 1850 1900 1950 2000 2050

PART 3:  Master Dating Series:                                                            11:05  Fri 30 Apr 2010  Page   4
------------------------------------------------------------------------------------------------------------------------------------
  Year  Value  No Ab    Year  Value  No Ab    Year  Value  No Ab    Year  Value  No Ab    Year  Value  No Ab    Year  Value  No Ab
  ------------------    ------------------    ------------------    ------------------    ------------------    ------------------
                        1800   .157   1       1850   .095  24       1900   .641  51       1950  -.042  58       2000 -1.835  58  7
                        1801 -1.343   1       1851   .032  25       1901   .292  51       1951  1.483  59       2001 -1.434  58  7
                        1802  -.567   1       1852  -.221  25       1902  1.459  51       1952  -.188  59       2002 -1.065  58  5
                        1803 -1.334   1       1853   .706  26       1903   .661  51       1953 -1.222  59       2003  -.713  58  2
                        1804   .739   1       1854  -.421  27       1904  -.487  53       1954  -.992  59       2004  -.133  58
                        1805 -1.814   1       1855 -1.099  27       1905  -.289  54       1955 -1.489  59       2005  1.255  58
```

```
                      1806 -1.820   1       1856  1.548  28       1906  1.130  54       1956 -1.918  59       2006  1.810  58
                      1807 -1.406   1       1857  -.231  28       1907  -.189  54       1957  -.885  59       2007   .334  58
                      1808  1.915   1       1858  -.231  29       1908   .364  54       1958 -1.248  59       2008   .076  58
                      1809  3.235   1       1859  -.523  30       1909  -.653  54       1959   .895  59       2009  -.256  57

                      1810  1.930   1       1860   .554  31       1910 -1.031  54       1960  1.135  59       2010  1.089  57
                      1811   .441   1       1861  -.463  31       1911   .033  54       1961   .495  59       2011   .864  56
                      1812  -.363   1       1862  1.506  31       1912   .110  54       1962   .432  59       2012   .242  55
                      1813   .689   1       1863   .993  33       1913  1.488  54       1963   .285  59       2013   .168  11
                      1814   .810   1       1864 -1.566  33       1914   .877  54       1964   .691  59
                      1815   .843   2       1865 -1.113  33       1915   .121  55       1965  1.250  59
                      1816   .107   3       1866  -.936  34       1916  1.418  55       1966  1.077  59
                      1817   .482   4       1867  -.083  34       1917   .807  55       1967   .460  59
                      1818  -.274   4       1868   .015  34       1918  -.971  55       1968  -.204  59
                      1819  -.319   5       1869   .195  34       1919  -.382  55       1969 -1.032  59

                      1820   .044   5       1870   .078  36       1920   .447  55       1970   .735  59
                      1821 -2.625   5       1871  -.556  36       1921  1.104  55       1971  -.181  59
                      1822 -1.115   6       1872  1.449  36       1922  -.265  55       1972  -.877  59
                      1823   .872   8       1873  -.027  38       1923  -.735  55       1973  -.996  59
                      1824   .550   8       1874 -1.657  39       1924  -.102  56       1974  -.888  59
                      1825   .308   8       1875  -.529  40       1925   .019  56       1975   .364  59
                      1826  -.690   8       1876   .586  40       1926 -1.752  56       1976  1.522  59
                      1827  -.184   9       1877  -.264  41       1927 -1.562  56       1977 -1.141  59
                      1828   .895   9       1878  1.073  41       1928  -.733  56       1978 -1.066  59  1
                      1829  -.418  10       1879  -.634  42       1929  -.205  56       1979 -1.028  59

                      1830   .567  11       1880  1.673  42       1930   .719  56       1980  1.449  59
                      1831  -.073  11       1881   .150  43       1931   .478  57       1981  -.329  59
                      1832   .979  11       1882   .039  44       1932   .034  57       1982  -.230  59
                      1833   .637  11       1883  -.183  45       1933   .330  57       1983  -.565  59
                      1834  -.411  12       1884   .632  45       1934   .311  57       1984 -2.135  59  3
                      1835  -.094  12       1885  -.017  45       1935  -.967  57       1985 -1.083  59
                      1836   .800  12       1886  -.466  47       1936  -.944  57       1986   .406  59
                      1837 -2.606  13       1887  -.499  47       1937  -.576  57       1987   .662  59
                      1838  -.287  14       1888   .662  47       1938  -.678  57       1988   .149  59
                      1839  -.256  14       1889   .949  48       1939  -.317  58       1989  -.154  59

                      1840 -1.760  15       1890   .360  48       1940  -.601  58       1990  -.066  59
                      1841  -.459  15       1891   .105  48       1941  1.226  58       1991   .545  58
1792   .622   1       1842   .151  15       1892   .471  48       1942   .485  58       1992   .790  58
1793   .861   1       1843  1.067  17       1893   .690  48       1943   .169  58       1993  2.311  58
1794  -.634   1       1844   .966  18       1894  -.127  49       1944   .534  58       1994   .691  58
1795 -3.914   1       1845   .601  19       1895 -1.348  49       1945   .629  58       1995  1.273  58
1796   .459   1       1846   .020  20       1896 -1.986  50       1946   .571  58       1996   .951  58
1797  3.476   1       1847  -.398  21       1897 -1.708  50       1947   .746  58       1997  -.453  58
1798   .329   1       1848   .896  22       1898  -.837  50       1948   .509  58       1998 -1.116  58  1
1799  -.893   1       1849   .858  22       1899  -.118  50       1949   .537  58       1999 -1.695  58  7
---------------------------------------------------------------------------------------------------------------------------------

PART 4:  Master Bar Plot:                                                                    11:05  Fri 30 Apr 2010  Page   5
```

Year Rel value	Year Rel value	Year Rel value	Year Rel value	Year Rel value	Year Rel value	Year Rel value	Year Rel value
	1800-----A	1850-----@	1900--------C	1950-----@	2000g		
	1801-e	1851-----@	1901------A	1951----------F	2001f		
	1802--b	1852----a	1902----------F	1952----a	2002-d		
	1803-e	1853--------C	1903--------C	1953-e	2003--c		
	1804--------C	1854---b	1904---b	1954-d	2004----a		
	1805g	1855-d	1905---a	1955f	2005----------E		
	1806g	1856----------F	1906---------E	1956h	2006----------G		
	1807-f	1857----a	1907----a	1957-d	2007------A		
	1808----------H	1858----a	1908------A	1958-e	2008-----@		
	1809----------M	1859---b	1909--c	1959---------D	2009----a		
	1810----------H	1860-------B	1910-d	1960---------E	2010---------D		
	1811-------B	1861---b	1911-----@	1961-------B	2011---------C		
	1812---a	1862----------F	1912-----@	1962-------B	2012------A		
	1813--------C	1863---------D	1913----------F	1963------A	2013-----A		
	1814--------C	1864f	1914---------D	1964--------C			
	1815---------C	1865-d	1915-----@	1965----------E			
	1816-----@	1866-d	1916----------F	1966---------D			
	1817-------B	1867----@	1917--------C	1967-------B			
	1818----a	1868-----@	1918-d	1968----a			
	1819---a	1869------A	1919---b	1969-d			
	1820-----@	1870-----@	1920-------B	1970--------C			
	1821k	1871--b	1921---------D	1971----a			
	1822-d	1872----------F	1922----a	1972-d			
	1823---------C	1873-----@	1923--c	1973-d			
	1824-------B	1874g	1924----@	1974-d			
	1825------A	1875---b	1925-----@	1975------A			
	1826--c	1876-------B	1926g	1976----------F			
	1827----a	1877----a	1927f	1977-e			
	1828---------D	1878---------D	1928--c	1978-d			
	1829---b	1879--c	1929----a	1979-d			
	1830-------B	1880----------G	1930--------C	1980----------F			
	1831-----@	1881-----A	1931-------B	1981---a			
	1832---------D	1882-----@	1932-----@	1982----a			
	1833--------C	1883----a	1933------A	1983--b			
	1834---b	1884--------C	1934------A	1984i			
	1835----@	1885-----@	1935-d	1985-d			
	1836--------C	1886---b	1936-d	1986------B			
	1837j	1887---b	1937--b	1987--------C			
	1838---a	1888--------C	1938--c	1988-----A			
	1839----a	1889---------D	1939---a	1989----a			
	1840g	1890------A	1940--b	1990-----@			
	1841---b	1891-----@	1941---------E	1991-------B			
1792--------B	1842-----A	1892-------B	1942-------B	1992--------C			
1793---------C	1843---------D	1893--------C	1943-----A	1993----------I			
1794--c	1844---------D	1894----a	1944-------B	1994--------C			
1795p	1845-------B	1895-e	1945--------C	1995----------E			
1796-------B	1846-----@	1896h	1946-------B	1996---------D			
1797----------N	1847---b	1897g	1947--------C	1997---b			
1798------A	1848---------D	1898--c	1948-------B	1998-d			

```
  1799-d         1849---------C  1899----@       1949-------B    1999g
```

PART 5: CORRELATION OF SERIES BY SEGMENTS: 11:05 Fri 30 Apr 2010 Page 5

Correlations of 40-year dated segments, lagged 20 years
Flags: A = correlation under .3665 but highest as dated; B = correlation higher at other than dated position

Seq	Series	Time_span	1800 1839	1820 1859	1840 1879	1860 1899	1880 1919	1900 1939	1920 1959	1940 1979	1960 1999	1980 2019
1	LC01-1C	1881 2013					.39	.64	.57	.51	.69	.73
2	LC01-2D	1851 2013			.60	.63	.51	.45	.64	.77	.84	.88
3	LC01-2E	1840 2012			.56	.57	.56	.44	.48	.71	.79	.74
4	LC01-3C	1905 2013						.44	.48	.55	.67	.53
5	LC01-3D	1823 2013		.62	.48	.40	.54	.38	.18A	.42	.32B	.25B
6	LC01-4C	1873 2013				.50	.62	.60	.59	.73	.73	.79
7	LC01-4D	1848 2013			.69	.71	.66	.60	.55	.45	.57	.61
8	LC01-5B	1843 2012			.46	.47	.52	.62	.51	.46	.65	.58
9	LC01-5C	1850 2013			.47	.43	.32A	.20B	.48	.65	.71	.62
10	LC01-5D	1886 2013					.37B	.45	.55	.65	.72	.55
11	LC01-5E	1819 2013	.51	.54	.42	.35A	.42	.55	.45	.44	.69	.61
12	LC01-8A	1815 2012	.39	.52	.55	.62	.57	.58	.61	.59	.41	.33A
13	LC01-9A	1915 2012						.31A	.34A	.48	.65	.73
14	LC01-9B	1939 2012							.60	.61	.47	.47
15	LC01-10A	1951 2012								.56	.58	.69
16	LC01-10B	1886 2012					.49	.49	.41	.68	.78	.78
17	LC01-11A	1896 2012					.35A	.33A	.44	.56	.66	.67
18	LC01-11B	1875 2012				.44	.44	.35A	.44	.59	.78	.70
19	LC01-12A	1883 2012					.43	.28A	.35A	.80	.82	.81
20	LC01-12B	1827 2012		.51	.49	.64	.43	.29A	.50	.83	.91	.87
21	LC01-13A	1860 2012				.37	.45	.46	.58	.59	.56	.57
22	LC01-13B	1847 2012			.45	.61	.73	.68	.66	.76	.62	.63
23	LC01-14	1838 2012		.41	.46	.52	.50	.47	.48	.53	.37	.42
24	LC01-16	1931 2012							.17B	.28B	.49	.44
25	LC01-18A	1874 2012				.45	.40	.39	.47	.41	.30B	.43B
26	LC01-18B	1870 2012				.48	.36A	.37	.52	.50	.52	.55
27	LC01-19A	1904 2012						.73	.66	.83	.47	.44
28	LC01-19B	1904 2012						.70	.73	.79	.63	.67
29	LC01-19C	1873 1990				.50	.55	.75	.73	.83	.80	
30	LC01-19D	1900 2012						.46	.65	.89	.72	.72
31	LC01-21A	1863 2012				.15B	.47	.60	.43	.54	.61	.62
32	LC01-21B	1866 2012				.39B	.56	.67	.64	.63	.63	.70
33	LC01-22	1924 2012							.49	.44	.50	.54
34	LC01-23A	1846 2012			.55	.52	.49	.53	.67	.53	.45	.56
35	LC01-24A	1856 2012			.20B	.46	.67	.47	.43	.48	.47	.36A
36	LC01-24B	1845 2008			.23B	.39	.52	.61	.40	.33B	.58	.63
37	LC01-25A	1870 2012				.40	.51	.75	.72	.69	.73	.57
38	LC01-25B	1882 2012					.45	.31A	.39	.63	.66	.73
39	LC01-26A	1879 2011				.24B	.27B	.52	.49	.62	.71	.72
40	LC01-26B	1792 2012	.24B	.30B	.32B	.45	.53	.47	.47	.45	.54	.56
41	LC01-28A	1822 2012		.62	.57	.61	.61	.49	.54	.63	.67	.63

42	LC01-28B	1817	2012	.41	.43	.58	.56	.41	.40	.64	.46	.32B	.30A
43	LC01-29A	1850	2012			.46	.42	.54	.61	.50	.60	.72	.74
44	LC01-29B	1816	2012	.41	.63	.63	.59	.49	.56	.69	.73	.70	.70
45	LC01-30A	1854	2012			.52	.52	.62	.46	.28A	.58	.72	.74
46	LC01-31A	1859	2012			.68	.69	.68	.56	.44	.57	.73	.75
47	LC01-32A	1844	2012			.54	.56	.51	.55	.54	.44	.55	.61
48	LC01-32B	1829	2012		.49	.60	.60	.47	.52	.46	.40	.62	.75
49	LC01-33A	1863	2012				.67	.73	.48	.40B	.63	.74	.74
50	LC01-34	1894	2012					.42	.35A	.40	.80	.70	.69
51	LC01-35A	1853	2013			.62	.62	.62	.64	.62	.63	.77	.76
52	LC01-35B	1837	2013		.43B	.56	.67	.61	.56	.62	.65	.79	.85
53	LC01-35C	1858	2012			.54	.53	.62	.67	.57	.54	.71	.75
54	LC01-35D	1834	2012		.84	.72	.63	.61	.63	.53	.70	.92	.91
55	LC01-36B	1877	2012				.57	.57	.66	.67	.38B	.38	.41
56	LC01-38A	1830	2012		.30A	.45	.40	.09B	.30B	.50	.55	.64	.67
57	LC01-39A	1889	2012					.35A	.33A	.32A	.75	.83	.80
58	LC01-39B	1823	2010		.59	.70	.66	.45	.33A	.48	.54	.63	.72
59	LC01-40B	1843	2012			.54	.47	.40	.13B	.17B	.28A	.53	.54
Av segment correlation				.39	.52	.52	.51	.50	.49	.51	.59	.63	.64

PART 6: POTENTIAL PROBLEMS: 11:05 Fri 30 Apr 2010 Page 6

For each series with potential problems the following diagnostics may appear:

[A] Correlations with master dating series of flagged 40-year segments of series filtered with 32-year spline,
at every point from ten years earlier (-10) to ten years later (+10) than dated

[B] Effect of those data values which most lower or raise correlation with master series
Symbol following year indicates value in series is greater (>) or lesser (<) than master series value

[C] Year-to-year changes very different from the mean change in other series

[D] Absent rings (zero values)

[E] Values which are statistical outliers from mean for the year

===

LC01-1C 1881 to 2013 133 years Series 1

[B] Entire series, effect on correlation (.515) is:
Lower 1883< -.078 1935> -.014 1969> -.011 1962< -.010 1941< -.010 1886> -.009 Higher 1984 .018 1902 .012

LC01-2D 1851 to 2013 163 years Series 2

[B] Entire series, effect on correlation (.640) is:
Lower 1907< -.025 1909> -.010 1918> -.009 1862< -.008 2010< -.006 1906< -.006 Higher 1977 .024 1864 .012

```
 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1907 -4.9 SD
=====================================================================================================================================

 LC01-2E   1840 to  2012     173 years                                                                                    Series   3

 [B] Entire series, effect on correlation (  .568) is:
       Lower   1881< -.018   1852< -.015   1926> -.014   1902< -.013   1933< -.010   1871> -.009  Higher   1864  .025   1993  .012

=====================================================================================================================================

 LC01-3C   1905 to  2013     109 years                                                                                    Series   4

 [B] Entire series, effect on correlation (  .510) is:
       Lower   1977> -.037   1935> -.018   2006< -.017   2007> -.017   1916< -.015   1926> -.014  Higher   1993  .023   1980  .022

=====================================================================================================================================

 LC01-3D   1823 to  2013     191 years                                                                                    Series   5

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----    ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1920 1959    0    .00 -.24  .14 -.09  .11  .12  .08 -.13  .14  .05  .18*-.19  .03  .07  .01 -.15  .08 -.20 -.17 -.19 -.14
    - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    1960 1999    5    .02 -.22 -.22 -.34  .14 -.09 -.18 -.16  .03  .14  .32| .23  .16 -.04  .02  .34*-.21  .19 -.21 -.08 -.25
    1974 2013   -6    .15  .00  .01 -.05  .27* .02 -.08 -.17  .04 -.17  .25|  -    -    -    -    -    -    -    -    -    -

 [B] Entire series, effect on correlation (  .396) is:
       Lower   2006< -.045   1970< -.022   1865< -.020   1833< -.013   1926> -.012   1981> -.011  Higher   1837  .047   1977  .019
     1920 to 1959 segment:
       Lower   1926> -.060   1941< -.051   1935> -.048   1933< -.030   1920< -.024   1951< -.021  Higher   1959  .078   1921  .045
     1960 to 1999 segment:
       Lower   1970< -.106   1981> -.057   1994> -.036   1995< -.025   1971> -.019   1987< -.018  Higher   1977  .116   1980  .054
     1974 to 2013 segment:
       Lower   2006< -.206   1981> -.043   1994> -.026   1995< -.024   2013> -.020   1987< -.017  Higher   1977  .114   2005  .058

 [C] Year-to-year changes diverging by over 4.0 std deviations:
       1864 1865  -5.0 SD

 [D]    1 Absent rings:  Year   Master  N series Absent
                         1999   -1.695      58       7

 [E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
       1865 -5.9 SD;    1970 -4.6 SD
=====================================================================================================================================

 LC01-4C   1873 to  2013     141 years                                                                                    Series   6

 [B] Entire series, effect on correlation (  .621) is:
       Lower   1873> -.016   1935> -.012   1909> -.011   1941< -.011   1877> -.010   1920< -.007  Higher   1977  .036   1926  .019
```

```
====================================================================================================================================

 LC01-4D   1848 to  2013     166 years                                                                                    Series   7

 [B] Entire series, effect on correlation (  .598) is:
      Lower   1977> -.020   1981> -.011   1956> -.010   1868< -.009   1874> -.009   1935> -.009  Higher   1864  .019   1926  .018

====================================================================================================================================

 LC01-5B   1843 to  2012     170 years                                                                                    Series   8

 [B] Entire series, effect on correlation (  .496) is:
      Lower   1878< -.037   2006< -.018   1844< -.018   1887> -.010   1959< -.009   1872< -.007  Higher   1864  .031   1926  .025

 [C] Year-to-year changes diverging by over 4.0 std deviations:
      1877 1878  -4.1 SD

 [E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
      1878 -5.4 SD;    1879 -6.0 SD
====================================================================================================================================

 LC01-5C   1850 to  2013     164 years                                                                                    Series   9

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
   ---------   ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
   1880 1919    0    .01 -.15  .21  .10 -.01  .16  .17 -.15  .02 -.24  .32*-.26 -.14  .16  .10  .02  .04 -.09  .11 -.08 -.13
   1900 1939    3   -.02 -.14  .28 -.01  .08  .22  .10  .00 -.28 -.02  .20|-.26 -.28  .32* .04 -.10 -.09 -.09  .05 -.09 -.13

 [B] Entire series, effect on correlation (  .467) is:
      Lower   2006< -.028   1864> -.015   1861> -.011   1907> -.011   1913< -.010   1877> -.010  Higher   1977  .051   1981  .014
    1880 to 1919 segment:
      Lower   1907> -.046   1918> -.038   1913< -.035   1887> -.028   1900< -.020   1885> -.019  Higher   1880  .062   1881  .047
    1900 to 1939 segment:
      Lower   1907> -.048   1913< -.040   1918> -.034   1900< -.027   1901< -.021   1915< -.011  Higher   1904  .036   1916  .034

====================================================================================================================================

 LC01-5D   1886 to  2013     128 years                                                                                    Series  10

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
   ---------   ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
   1886 1925   -10    .39* .16  .21 -.04  .08  .07 -.13 -.20 -.32 -.01  .37|-.09 -.20  .21  .03 -.16 -.27 -.01  .30  .14  .11

 [B] Entire series, effect on correlation (  .506) is:
      Lower   2006< -.053   2013> -.014   1922> -.014   1959< -.010   2008< -.010   1923> -.009  Higher   1984  .028   1977  .026
    1886 to 1925 segment:
      Lower   1922> -.048   1923> -.031   1909> -.029   1896> -.014   1914< -.013   1910> -.012  Higher   1918  .036   1904  .033

====================================================================================================================================
```

```
LC01-5E   1819 to  2013     195 years                                                                                    Series  11

[A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
   ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
   1860 1899    0    .01  .10  .05  .08  .09 -.04 -.17 -.17  .17 -.13  .35*-.04 -.04 -.10  .10 -.29 -.16 -.02 -.24  .08  .10

[B] Entire series, effect on correlation (  .497) is:
      Lower   1824< -.016   1872< -.015   1840> -.015   1896> -.013   1819> -.011   1977> -.010  Higher   1837  .057   1984  .011
    1860 to 1899 segment:
      Lower   1872< -.083   1896> -.063   1884< -.052   1892< -.014   1868> -.011   1891> -.011  Higher   1880  .079   1862  .034

[E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      1896 +3.3 SD
====================================================================================================================================

LC01-8A   1815 to  2012     198 years                                                                                    Series  12

[A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
   ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
   1973 2012    0   -.27  .08 -.11 -.06 -.15  .18  .07 -.07 -.06 -.06  .33* .30    -    -    -    -    -    -    -    -    -

[B] Entire series, effect on correlation (  .524) is:
      Lower   1993< -.014   1994> -.010   1976< -.009   1881> -.008   1824< -.008   1816> -.007  Higher   1821  .015   1880  .011
    1973 to 2012 segment:
      Lower   1993< -.056   1994> -.039   1976< -.032   2009> -.013   1983> -.010   1986< -.009  Higher   1984  .074   2010  .024

[D]    7 Absent rings:  Year   Master  N series Absent
                        1984   -2.135      59       3
                        1998   -1.116      58       1
                        1999   -1.695      58       7
                        2000   -1.835      58       7
                        2001   -1.434      58       7
                        2002   -1.065      58       5
                        2003    -.713      58       2

====================================================================================================================================

LC01-9A   1915 to  2012      98 years                                                                                    Series  13

[A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
   ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
   1915 1954    0   -.24 -.09  .23 -.05 -.22  .05  .24  .03 -.20 -.36  .31* .10 -.13  .03  .24  .17  .10 -.30 -.17  .30  .01
   1920 1959    0   -.28 -.09  .27 -.09 -.15 -.01  .09 -.03 -.28 -.40  .34* .05 -.05  .16  .19  .11  .13 -.21 -.11  .28  .01

[B] Entire series, effect on correlation (  .464) is:
      Lower   1943< -.032   1930< -.022   1981> -.016   1936> -.016   1969> -.013   1972> -.012  Higher   1977  .033   1980  .025
    1915 to 1954 segment:
      Lower   1943< -.045   1930< -.044   1936> -.032   1918> -.027   1927> -.021   1947< -.020  Higher   1952  .102   1951  .040
    1920 to 1959 segment:
      Lower   1943< -.050   1930< -.046   1936> -.031   1947< -.020   1927> -.020   1937> -.017  Higher   1952  .088   1951  .039
```

```
 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1937 +3.1 SD
==================================================================================================================================

 LC01-9B   1939 to  2012      74 years                                                                                    Series  14

 [B] Entire series, effect on correlation (  .481) is:
       Lower   1961< -.041   1993< -.019   1946< -.018   1981> -.017   1989< -.012   1992< -.011  Higher   1977  .050   1951  .024

==================================================================================================================================

 LC01-10A  1951 to  2012      62 years                                                                                    Series  15

 [B] Entire series, effect on correlation (  .608) is:
       Lower   1967< -.037   1968< -.026   1979< -.021   1981> -.018   1956> -.016   1978> -.013  Higher   1977  .033   1984  .020

==================================================================================================================================

 LC01-10B  1886 to  2012     127 years                                                                                    Series  16

 [B] Entire series, effect on correlation (  .561) is:
       Lower   1935> -.023   1907< -.018   1896> -.013   1921< -.012   1889< -.011   1947< -.011  Higher   1980  .015   1918  .014

==================================================================================================================================

 LC01-11A  1896 to  2012     117 years                                                                                    Series  17

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1896 1935    0   -.03 -.12 -.02  .08 -.04 -.13  .07  .13 -.09  .07  .35*-.22 -.04  .13 -.14 -.13 -.15 -.07 -.02  .17 -.08
    1900 1939    0    .00 -.13  .02  .07 -.09 -.13  .13  .17 -.07  .08  .33*-.25 -.06  .12 -.14 -.16 -.10 -.12 -.04  .15 -.03

 [B] Entire series, effect on correlation (  .524) is:
       Lower   1929< -.065   1918> -.023   1977> -.013   1994> -.012   1904> -.008   1928> -.008  Higher   1926  .022   1981  .018
     1896 to 1935 segment:
       Lower   1929< -.123   1918> -.057   1904> -.020   1927> -.017   1903> -.013   1928> -.012  Higher   1926  .078   1902  .036
     1900 to 1939 segment:
       Lower   1929< -.116   1918> -.062   1904> -.022   1927> -.019   1903> -.014   1928> -.014  Higher   1926  .083   1902  .039

==================================================================================================================================

 LC01-11B  1875 to  2012     138 years                                                                                    Series  18

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1900 1939    0    .03  .29  .02 -.30 -.06  .07 -.24 -.35  .15  .30  .35* .01  .15  .21 -.06 -.06 -.23 -.10 -.05  .23 -.08

 [B] Entire series, effect on correlation (  .546) is:
       Lower   1877< -.018   1926> -.015   1952> -.011   1907> -.010   2011< -.008   1972> -.007  Higher   1993  .017   1984  .016
     1900 to 1939 segment:
       Lower   1926> -.044   1907> -.034   1922> -.022   1904> -.021   1924< -.021   1938> -.016  Higher   1935  .065   1909  .051
```

```
===========================================================================================================================

 LC01-12A  1883 to  2012     130 years                                                                             Series  19

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1900 1939    0   -.03  .08  .03 -.27  .12  .06 -.12 -.09 -.09 -.13  .28*-.04 -.11  .12  .16  .07  .11 -.04 -.02 -.01 -.09
    1920 1959    0    .01 -.11  .19 -.13  .30  .22 -.05  .03 -.13 -.20  .35*-.25  .01  .25 -.04 -.04  .04 -.27 -.06 -.33 -.03

 [B] Entire series, effect on correlation (  .580) is:
       Lower   1932< -.022   1926> -.017   1935> -.016   1887< -.016   1927> -.014   1885> -.011  Higher   1977  .051   1902  .012
     1900 to 1939 segment:
       Lower   1932< -.048   1935> -.042   1927> -.039   1926> -.030   1936> -.019   1931< -.018  Higher   1902  .089   1918  .036
     1920 to 1959 segment:
       Lower   1932< -.054   1935> -.046   1926> -.044   1927> -.038   1944< -.020   1931< -.019  Higher   1951  .048   1959  .044

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1927 +3.2 SD
===========================================================================================================================

 LC01-12B  1827 to  2012     186 years                                                                             Series  20

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1900 1939    0   -.15  .09  .13  .09  .09  .12 -.01 -.10 -.17 -.20  .29*-.04  .12  .07  .21  .02 -.14  .18  .06  .17  .25

 [B] Entire series, effect on correlation (  .615) is:
       Lower   1840> -.027   1830< -.025   1916< -.012   1904> -.010   1833< -.009   1933< -.008  Higher   1837  .045   1977  .027
     1900 to 1939 segment:
       Lower   1916< -.059   1904> -.049   1933< -.038   1900< -.027   1927> -.026   1937> -.022  Higher   1935  .064   1918  .060

===========================================================================================================================

 LC01-13A  1860 to  2012     153 years                                                                             Series  21

 [B] Entire series, effect on correlation (  .508) is:
       Lower   1889< -.028   1936< -.015   1977> -.015   1874> -.013   1861> -.013   1865> -.010  Higher   1981  .014   1880  .013

===========================================================================================================================

 LC01-13B  1847 to  2012     166 years                                                                             Series  22

 [B] Entire series, effect on correlation (  .581) is:
       Lower   1980< -.039   2005< -.012   1857> -.012   1848< -.011   1878< -.011   1970< -.009  Higher   1977  .040   1864  .013

 [C] Year-to-year changes diverging by over 4.0 std deviations:
       1979 1980  -4.6 SD

===========================================================================================================================
```

```
LC01-14   1838 to  2012     175 years                                                                                    Series  23

[B] Entire series, effect on correlation (  .438) is:
      Lower   1935> -.019   1993< -.015   1851< -.009   1861> -.009   1873> -.009   1856< -.008  Higher   1864  .037   1840  .023

[D]    2 Absent rings:  Year   Master  N series Absent
                        1999   -1.695      58       7
                        2000   -1.835      58       7

[E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      1864 -5.1 SD
=====================================================================================================================================

LC01-16   1931 to  2012      82 years                                                                                    Series  24

[A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
   ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
   1931 1970   10    .06  .27  .25  .07 -.07 -.08 -.19 -.25 -.05 -.12  .17| .10 -.30 -.17 -.05  .07 -.05 -.06 -.07  .12  .38*
   1940 1979   10    .10  .16  .29 -.09  .01  .04 -.12 -.16 -.16 -.33  .28| .08 -.28 -.36  .07  .00  .08  .02 -.11 -.03  .36*

[B] Entire series, effect on correlation (  .346) is:
      Lower   1953> -.026   1951< -.026   1998> -.025   1991< -.021   2009< -.015   2005< -.013  Higher   1984  .045   1977  .044
    1931 to 1970 segment:
      Lower   1953> -.068   1951< -.063   1952> -.029   1955> -.027   1964< -.026   1944< -.026  Higher   1935  .096   1959  .080
    1940 to 1979 segment:
      Lower   1951< -.058   1953> -.054   1944< -.026   1964< -.026   1952> -.023   1955> -.020  Higher   1977  .137   1959  .056

[E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      1998 +3.2 SD
=====================================================================================================================================

LC01-18A  1874 to  2012     139 years                                                                                    Series  25

[A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
   ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
   1960 1999   -4    .22  .05 -.05 -.15  .07  .23  .43*-.26  .04 -.15  .30|-.22 -.05 -.30 -.17  .03 -.15 -.12 -.08  .04  .13
   1973 2012  -10    .45* .13 -.04 -.20 -.08 -.01  .29 -.34  .13 -.06  .43|-.31    -    -    -    -    -    -    -    -    -

[B] Entire series, effect on correlation (  .412) is:
      Lower   1935> -.017   1977> -.016   1874> -.015   1971> -.015   1997> -.014   1952> -.010  Higher   1980  .020   1984  .019
    1960 to 1999 segment:
      Lower   1971> -.056   1997> -.049   1977> -.036   1967< -.034   1986< -.025   1960< -.025  Higher   1984  .082   1980  .077
    1973 to 2012 segment:
      Lower   1977> -.057   1997> -.055   1993< -.027   1986< -.026   2011< -.019   1992< -.016  Higher   1984  .063   1980  .063

[D]    1 Absent rings:  Year   Master  N series Absent
                        1984   -2.135      59       3

[E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      1879 -4.7 SD
=====================================================================================================================================
```

```
LC01-18B  1870 to  2012     143 years                                                                                    Series  26

[A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
   ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
   1880 1919    0    .02 -.01  .09 -.02 -.02  .09  .11 -.24  .18 -.21  .36* .06 -.17 -.20  .04  .19 -.07 -.18  .06  .23 -.08

[B] Entire series, effect on correlation (  .501) is:
      Lower   1907> -.024   1953> -.017   1895> -.015   1952> -.014   1914< -.013   1886> -.011  Higher   1984  .026   1926  .017
    1880 to 1919 segment:
      Lower   1907> -.083   1895> -.051   1886> -.036   1914< -.034   1900< -.031   1916< -.026  Higher   1896  .083   1913  .037

[D]    1 Absent rings:  Year   Master  N series Absent
                        1984   -2.135      59      3

[E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      1953 +3.4 SD
==================================================================================================================================

LC01-19A  1904 to  2012     109 years                                                                                    Series  27

[B] Entire series, effect on correlation (  .586) is:
      Lower   1990< -.039   1984> -.025   1993< -.017   2012< -.016   1928< -.015   1947< -.014  Higher   1977  .057   1926  .023

==================================================================================================================================

LC01-19B  1904 to  2012     109 years                                                                                    Series  28

[B] Entire series, effect on correlation (  .672) is:
      Lower   1997> -.012   1991< -.011   1992< -.009   1937> -.009   1993< -.007   1972> -.007  Higher   1977  .048   1926  .016

==================================================================================================================================

LC01-19C  1873 to  1990     118 years                                                                                    Series  29

[B] Entire series, effect on correlation (  .680) is:
      Lower   1873> -.021   1981> -.019   1947< -.018   1887< -.013   1888< -.013   1890< -.012  Higher   1977  .042   1941  .010

==================================================================================================================================

LC01-19D  1900 to  2012     113 years                                                                                    Series  30

[B] Entire series, effect on correlation (  .607) is:
      Lower   1978< -.020   1903< -.019   1912< -.014   1922> -.014   1930< -.013   1984> -.011  Higher   1977  .054   1902  .011

[D]    1 Absent rings:  Year   Master  N series Absent
                        1978   -1.066      59      1

[E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      1978 -4.8 SD
==================================================================================================================================
```

```
LC01-21A  1863 to  2012     150 years                                                                                    Series  31

[A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
   ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
   1863 1902   -2   -.35  .27 -.10  .30 -.18 -.21 -.04  .00  .36*-.14  .15|-.05  .19 -.11  .05  .05 -.16 -.11  .04  .07 -.22

[B] Entire series, effect on correlation (  .430) is:
      Lower   1866< -.023   1872< -.017   1981> -.016   1874> -.016   1951< -.015   1880< -.010  Higher   1977  .027   1926  .016
    1863 to 1902 segment:
      Lower   1872< -.041   1874> -.039   1892< -.023   1865> -.017   1880< -.016   1879> -.015  Higher   1902  .029   1884  .025

=====================================================================================================================================

LC01-21B  1866 to  2012     147 years                                                                                    Series  32

[A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
   ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
   1866 1905   -6    .00  .10 -.26 -.13  .42*-.12  .06 -.21  .27 -.22  .39|-.08 -.06  .02  .33 -.23 -.12  .00 -.08  .05 -.30

[B] Entire series, effect on correlation (  .573) is:
      Lower   1870< -.060   1930< -.014   1969> -.009   1880< -.009   1904> -.008   1976< -.007  Higher   1977  .022   1926  .021
    1866 to 1905 segment:
      Lower   1870< -.131   1880< -.025   1904> -.024   1892< -.015   1871> -.012   1886> -.010  Higher   1879  .052   1872  .040

=====================================================================================================================================

LC01-22   1924 to  2012      89 years                                                                                    Series  33

[B] Entire series, effect on correlation (  .529) is:
      Lower   1977> -.064   1931< -.013   1982< -.011   1924< -.010   1978> -.009   1936> -.009  Higher   1926  .038   1984  .036

=====================================================================================================================================

LC01-23A  1846 to  2012     167 years                                                                                    Series  34

[B] Entire series, effect on correlation (  .521) is:
      Lower   1900< -.023   1980< -.018   1976< -.012   1874> -.011   1871< -.010   1857> -.007  Higher   1864  .026   1862  .010

=====================================================================================================================================

LC01-24A  1856 to  2012     157 years                                                                                    Series  35

[A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
   ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
   1856 1895    8    .04  .23  .07 -.01 -.15 -.14 -.01  .00  .08 -.15  .20| .16  .13 -.11 -.08 -.10  .07 -.22  .29*-.06  .12
   - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
   1973 2012    0   -.10 -.08 -.09  .11  .25  .00 -.09 -.19  .15  .19  .36* .08    -    -    -    -    -    -    -    -    -

[B] Entire series, effect on correlation (  .397) is:
      Lower   1856< -.049   1926> -.019   1934< -.014   1861> -.013   1857> -.012   1953> -.009  Higher   1951  .014   1941  .013
```

```
    1856 to 1895 segment:
      Lower   1856< -.178   1861> -.043   1857> -.038   1867< -.025   1879> -.016   1883> -.012  Higher   1880  .054   1872  .053
    1973 to 2012 segment:
      Lower   1975< -.037   1981> -.031   2006< -.031   1994> -.029   1976< -.020   2012> -.019  Higher   1980  .038   1993  .035

 [C] Year-to-year changes diverging by over 4.0 std deviations:
      1856 1857   4.4 SD

 [D]    4 Absent rings:  Year   Master  N series Absent
                         1999   -1.695      58       7
                         2000   -1.835      58       7
                         2001   -1.434      58       7
                         2002   -1.065      58       5

====================================================================================================================================

 LC01-24B  1845 to  2008     164 years                                                                                   Series  36

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1845 1884   -7    .23 -.05 -.01  .35*-.22 -.08  .04 -.15  .02 -.11  .23|-.12 -.05  .15 -.05 -.14  .19 -.12  .25 -.37  .27
    - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    1940 1979   10    .08 -.18 -.18 -.21  .12  .11 -.09 -.03  .22 -.12  .33|-.09 -.19 -.11  .15  .19  .03 -.05  .09 -.08  .43*

 [B] Entire series, effect on correlation (  .405) is:
      Lower   1851< -.023   1857> -.019   1864> -.018   1977> -.011   1879> -.010   1948< -.010  Higher   1993  .014   1941  .014
    1845 to 1884 segment:
      Lower   1851< -.059   1857> -.051   1864> -.042   1879> -.025   1855> -.024   1846> -.023  Higher   1873  .039   1874  .038
    1940 to 1979 segment:
      Lower   1977> -.048   1948< -.035   1953> -.031   1970< -.020   1942< -.017   1945< -.016  Higher   1941  .073   1951  .045

 [D]    5 Absent rings:  Year   Master  N series Absent
                         1999   -1.695      58       7
                         2000   -1.835      58       7
                         2001   -1.434      58       7
                         2002   -1.065      58       5
                         2003    -.713      58       2

====================================================================================================================================

 LC01-25A  1870 to  2012     143 years                                                                                   Series  37

 [B] Entire series, effect on correlation (  .567) is:
      Lower   2009< -.041   1874> -.024   1880< -.010   1898> -.009   1934< -.008   1888< -.008  Higher   1926  .025   1993  .017

====================================================================================================================================

 LC01-25B  1882 to  2012     131 years                                                                                   Series  38

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
```

```
   1900 1939    0    .19  .00  .20 -.28 -.03  .11 -.18 -.25  .22 -.01  .31* .13 -.23 -.11  .01 -.09  .10  .05  .15  .10 -.14

[B] Entire series, effect on correlation (  .525) is:
      Lower   1928< -.020   1926> -.014   1907> -.013   1884< -.012   1935> -.012   1927> -.010  Higher   1993  .020   1981  .017
    1900 to 1939 segment:
      Lower   1928< -.042   1907> -.037   1926> -.035   1935> -.034   1927> -.030   1934< -.023  Higher   1913  .042   1909  .039

====================================================================================================================================

LC01-26A  1879 to  2011     133 years                                                                                    Series  39

[A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
   ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
   1879 1918    8    .03 -.14  .21 -.03 -.06 -.19  .18  .01  .04 -.29  .24| .04 -.10 -.25  .00  .16  .15 -.05  .37* .15 -.06
   1880 1919    8    .02 -.14  .23 -.05 -.03 -.17  .17  .01  .06 -.32  .27| .02 -.07 -.25  .00  .15  .16 -.06  .37* .14 -.08

[B] Entire series, effect on correlation (  .423) is:
      Lower   1889< -.110   1899< -.014   1879> -.013   1936> -.012   1965< -.010   1916< -.009  Higher   1977  .032   1993  .018
    1879 to 1918 segment:
      Lower   1889< -.211   1879> -.035   1896> -.023   1899< -.022   1916< -.017   1885> -.011  Higher   1918  .038   1880  .029
    1880 to 1919 segment:
      Lower   1889< -.222   1896> -.026   1899< -.022   1916< -.018   1897> -.013   1885> -.013  Higher   1918  .038   1880  .027

[C] Year-to-year changes diverging by over 4.0 std deviations:
      1888 1889  -4.1 SD

====================================================================================================================================

LC01-26B  1792 to  2012     221 years                                                                                    Series  40

[*] Early part of series cannot be checked from 1792 to 1814 -- not matched by another series

[A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
   ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
   1815 1854   -5   -.01  .02  .12 -.02 -.06  .43*-.01  .04  .26 -.25  .24|-.11 -.24  .09 -.29  .32 -.22 -.10  .11  .00 -.03
   1820 1859   -5   -.04  .00  .09 -.11 -.13  .42*-.08  .06  .13 -.22  .30|-.25 -.05  .08 -.19  .25 -.15 -.20  .01  .12  .02
   1840 1879   -5   -.02  .10 -.03 -.14 -.08  .37*-.12  .11  .00 -.18  .32|-.07 -.09 -.04 -.01  .21 -.08 -.15 -.12  .07  .30

[B] Entire series, effect on correlation (  .411) is:
      Lower   1842< -.034   1869< -.022   1832< -.012   1819> -.007   1976< -.007   1909> -.006  Higher   1864  .017   1821  .014
    1815 to 1854 segment:
      Lower   1842< -.106   1832< -.034   1819> -.022   1816> -.013   1840> -.009   1833> -.009  Higher   1821  .062   1837  .030
    1820 to 1859 segment:
      Lower   1842< -.094   1832< -.030   1840> -.016   1857> -.012   1833> -.009   1834> -.009  Higher   1821  .044   1856  .028
    1840 to 1879 segment:
      Lower   1842< -.099   1869< -.058   1840> -.018   1871> -.016   1877> -.016   1861> -.015  Higher   1864  .061   1862  .041

[E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      1855 -4.8 SD
====================================================================================================================================
```

```
LC01-28A  1822 to  2012     191 years                                                                                    Series  41

[B] Entire series, effect on correlation (  .596) is:
      Lower   1822< -.025   1907> -.009   1922> -.009   1879> -.009   1847> -.008   1882< -.008  Higher   1837  .053   1840  .013

[D]    1 Absent rings:  Year   Master  N series Absent
                        2002   -1.065      58       5

====================================================================================================================================

LC01-28B  1817 to  2012     196 years                                                                                    Series  42

[A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
   ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
   1960 1999    3   -.02 -.21 -.26 -.05  .11 -.06  .05 -.16 -.08 -.01  .32| .05 -.07  .42* .05  .18  .13 -.02  .04 -.05  .06
   1973 2012    0    .13 -.23 -.24 -.06  .03 -.07  .05 -.18 -.10 -.05  .30* .03    -    -    -    -    -    -    -    -    -

[B] Entire series, effect on correlation (  .445) is:
      Lower   1976< -.019   1994< -.011   1977> -.011   1837> -.010   1818> -.009   1984> -.009  Higher   1864  .024   1993  .015
    1960 to 1999 segment:
      Lower   1976< -.071   1977> -.045   1984> -.034   1975< -.018   1979> -.016   1996< -.011  Higher   1993  .078   1965  .023
    1973 to 2012 segment:
      Lower   1976< -.063   1977> -.052   1984> -.038   1979> -.016   1975< -.015   1996< -.009  Higher   1993  .079   2010  .022

[D]    2 Absent rings:  Year   Master  N series Absent
                        2001   -1.434      58       7
                        2002   -1.065      58       5

====================================================================================================================================

LC01-29A  1850 to  2012     163 years                                                                                    Series  43

[B] Entire series, effect on correlation (  .573) is:
      Lower   1950< -.021   1864> -.018   1881> -.012   1898< -.011   1884< -.009   1994> -.009  Higher   1993  .011   1981  .010

====================================================================================================================================

LC01-29B  1816 to  2012     197 years                                                                                    Series  44

[B] Entire series, effect on correlation (  .591) is:
      Lower   1816< -.024   1955> -.010   1849< -.010   1819< -.010   1881> -.008   1824> -.008  Higher   1977  .027   1837  .026

[D]    3 Absent rings:  Year   Master  N series Absent
                        1999   -1.695      58       7
                        2000   -1.835      58       7
                        2001   -1.434      58       7

====================================================================================================================================

LC01-30A  1854 to  2012     159 years                                                                                    Series  45
```

```
 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
   ---------   ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
   1920 1959    0    .07  .07  .12  .25 -.05  .07  .22  .13 -.25  .16  .28*-.04 -.28  .01 -.09 -.31 -.26 -.15 -.03  .07  .23

 [B] Entire series, effect on correlation (  .562) is:
       Lower   1861> -.020   1926> -.018   1879> -.015   1941< -.012   1907> -.012   1981> -.011  Higher   1977  .038   1993  .012
     1920 to 1959 segment:
       Lower   1926> -.078   1941< -.053   1952> -.039   1938> -.023   1959< -.020   1950> -.019  Higher   1951  .091   1935  .056

 [C] Year-to-year changes diverging by over 4.0 std deviations:
       1977 1978   4.2 SD

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1977 -4.6 SD
==================================================================================================================================

 LC01-31A  1859 to  2012     154 years                                                                                 Series  46

 [B] Entire series, effect on correlation (  .624) is:
       Lower   1926> -.023   1959< -.011   1902< -.010   1927< -.010   1890< -.008   1866> -.007  Higher   1880  .010   1993  .010

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1864 -5.0 SD
==================================================================================================================================

 LC01-32A  1844 to  2012     169 years                                                                                 Series  47

 [B] Entire series, effect on correlation (  .531) is:
       Lower   1977> -.021   1864> -.012   1858> -.011   1951< -.009   1948< -.009   1997> -.009  Higher   1880  .012   1874  .011

==================================================================================================================================

 LC01-32B  1829 to  2012     184 years                                                                                 Series  48

 [B] Entire series, effect on correlation (  .552) is:
       Lower   1952> -.011   1953> -.011   1907> -.010   1921< -.009   1965< -.008   1881> -.008  Higher   1874  .011   1926  .009

==================================================================================================================================

 LC01-33A  1863 to  2012     150 years                                                                                 Series  49

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
   ---------   ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
   1920 1959   -1    .03  .06 -.07 -.25 -.39  .03  .00  .06 -.11  .42* .40| .07  .00  .13 -.12  .02  .09 -.10  .08 -.08 -.11

 [B] Entire series, effect on correlation (  .600) is:
       Lower   1926> -.032   1927< -.021   1870< -.020   1947< -.016   1958> -.009   1963< -.009  Higher   1977  .019   1874  .011
     1920 to 1959 segment:
       Lower   1926> -.127   1947< -.048   1958> -.032   1927< -.020   1942> -.012   1929< -.009  Higher   1941  .039   1956  .037

==================================================================================================================================
```

```
LC01-34   1894 to  2012     119 years                                                                                    Series  50

[A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
   ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
   1900 1939    0    .12 -.11  .04 -.15 -.15  .03  .03 -.04  .07 -.01  .35* .01 -.13  .08  .08 -.10 -.25 -.21 -.02 -.10 -.13

[B] Entire series, effect on correlation (  .500) is:
      Lower   1937< -.084   1981> -.023   1926> -.018   1936> -.012   1894> -.010   1895> -.009  Higher   1977  .032   1993  .014
    1900 to 1939 segment:
      Lower   1937< -.130   1926> -.052   1936> -.028   1906< -.013   1909> -.008   1932> -.007  Higher   1913  .036   1922  .035

[C] Year-to-year changes diverging by over 4.0 std deviations:
      1936 1937  -4.4 SD

==================================================================================================================================

LC01-35A  1853 to  2013     161 years                                                                                    Series  51

[B] Entire series, effect on correlation (  .665) is:
      Lower   1864> -.019   1907> -.015   1951< -.012   1871< -.010   1977> -.008   1870> -.007  Higher   1874  .010   1980  .009

==================================================================================================================================

LC01-35B  1837 to  2013     177 years                                                                                    Series  52

[A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
   ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
   1837 1876   -3   -.03 -.05 -.13 -.09  .16 -.12 -.06  .51*-.15 -.02  .43|-.23 -.10 -.12 -.02  .02  .02  .15 -.25 -.05  .15

[B] Entire series, effect on correlation (  .607) is:
      Lower   1837> -.044   1909> -.019   1873> -.012   1840< -.009   1843< -.007   1857> -.007  Higher   1993  .010   1980  .010
    1837 to 1876 segment:
      Lower   1837> -.104   1873> -.026   1843< -.020   1875< -.015   1857> -.013   1847> -.011  Higher   1856  .036   1864  .033

==================================================================================================================================

LC01-35C  1858 to  2012     155 years                                                                                    Series  53

[B] Entire series, effect on correlation (  .615) is:
      Lower   1864> -.020   1951< -.016   1907> -.015   1868> -.014   1958> -.009   1999> -.008  Higher   1980  .011   1993  .010

[E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      1868 +4.0 SD
==================================================================================================================================

LC01-35D  1834 to  2012     179 years                                                                                    Series  54

[B] Entire series, effect on correlation (  .753) is:
      Lower   1875< -.011   1951< -.009   1858< -.009   1957< -.007   1953> -.006   1885< -.005  Higher   1837  .034   1977  .008
```

```
 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1920 +3.2 SD
==================================================================================================================================

 LC01-36B  1877 to  2012     136 years                                                                                    Series  55

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1940 1979    6    .10  .16 -.15 -.23  .06  .00  .11 -.11 -.37  .17  .38| .19 -.04  .05  .24 -.03  .39* .01 -.16 -.21 -.09

 [B] Entire series, effect on correlation (  .488) is:
       Lower   1978< -.043   1980< -.016   1979> -.015   1965< -.015   2010< -.013   1911< -.010  Higher   1977  .046   1926  .013
     1940 to 1979 segment:
       Lower   1978< -.088   1979> -.039   1965< -.035   1974> -.022   1975< -.022   1969> -.013  Higher   1977  .169   1959  .040

 [C] Year-to-year changes diverging by over 4.0 std deviations:
       1978 1979   6.5 SD

 [D]    2 Absent rings:  Year   Master  N series Absent
                         2000   -1.835      58       7
                         2001   -1.434      58       7

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1978 -7.4 SD
==================================================================================================================================

 LC01-38A  1830 to  2012     183 years                                                                                    Series  56

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1830 1869    0   -.01  .13 -.21  .08 -.01 -.08  .08 -.22  .09 -.09  .30*-.46 -.02  .15 -.03  .11  .07 -.01  .07  .18 -.16
    - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    1880 1919   -5   -.14  .00  .03  .19 -.15  .40* .00  .12 -.16  .15  .09|-.10 -.42 -.09  .03  .07  .02  .02  .10  .13  .09
    1900 1939   -4   -.28 -.24  .16  .19 -.03  .08  .40* .29  .00 -.17  .30| .02 -.31 -.09  .02  .16  .06  .16 -.03  .13 -.04

 [B] Entire series, effect on correlation (  .415) is:
       Lower   1886< -.016   1837> -.013   1918> -.011   1864> -.011   1902< -.011   1907> -.009  Higher   1926  .017   1874  .016
     1830 to 1869 segment:
       Lower   1851< -.038   1855> -.029   1864> -.026   1858> -.024   1839> -.020   1849< -.012  Higher   1857  .019   1836  .017
     1880 to 1919 segment:
       Lower   1902< -.047   1918> -.043   1907> -.038   1896> -.030   1881> -.029   1894> -.016  Higher   1886  .054   1916  .037
     1900 to 1939 segment:
       Lower   1918> -.073   1902< -.065   1907> -.063   1936> -.028   1930< -.023   1900< -.020  Higher   1926  .169   1916  .043

 [D]    3 Absent rings:  Year   Master  N series Absent
                         1999   -1.695      58       7
                         2000   -1.835      58       7
                         2001   -1.434      58       7

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1837 +3.5 SD
```

```
===================================================================================================================

 LC01-39A  1889 to  2012     124 years                                                                    Series  57

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1889 1928    0    .33  .02  .26 -.02  .03  .00 -.06 -.40 -.40 -.28  .35*-.11 -.09  .35  .26 -.10 -.04 -.03  .18 -.09 -.12
    1900 1939    0    .22 -.12  .06  .14 -.07 -.11  .08 -.05 -.24 -.24  .33*-.32 -.21  .22  .11 -.17  .03  .10  .12 -.03 -.16
    1920 1959    0   -.04 -.35 -.09 -.02 -.04 -.03  .17  .30  .08  .01  .32*-.16  .07  .08 -.29 -.11 -.08 -.26 -.38 -.16 -.29

 [B] Entire series, effect on correlation (  .589) is:
       Lower   1941< -.027   1927> -.022   1891< -.014   1926> -.010   1898> -.009   2009> -.008  Higher   1977  .057   1984  .015
     1889 to 1928 segment:
       Lower   1927> -.059   1891< -.038   1910> -.020   1898> -.019   1920< -.016   1897> -.014  Higher   1913  .052   1918  .048
     1900 to 1939 segment:
       Lower   1927> -.077   1910> -.027   1923> -.018   1920< -.015   1935> -.014   1929< -.013  Higher   1913  .065   1918  .057
     1920 to 1959 segment:
       Lower   1941< -.101   1927> -.071   1920< -.018   1947< -.017   1929< -.016   1939< -.016  Higher   1953  .044   1956  .035

 [E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
       1898 +3.3 SD;    1927 +3.7 SD
===================================================================================================================

 LC01-39B  1823 to  2010     188 years                                                                    Series  58

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1900 1939    0    .18  .08  .18  .09 -.07 -.11 -.21 -.21 -.19 -.17  .33* .00 -.05  .17  .22  .01 -.08 -.19  .15 -.09 -.40

 [B] Entire series, effect on correlation (  .569) is:
       Lower   1831< -.027   1826> -.020   1965< -.013   1977> -.013   1896> -.011   1823< -.011  Higher   1837  .055   1874  .010
     1900 to 1939 segment:
       Lower   1927> -.047   1902< -.037   1920< -.026   1926> -.022   1909> -.016   1932> -.015  Higher   1913  .070   1918  .040

 [E] Outliers     3   3.0 SD above or -4.5 SD below mean for year
       1826 +3.3 SD;    1874 -5.2 SD;    1897 +3.3 SD
===================================================================================================================

 LC01-40B  1843 to  2012     170 years                                                                    Series  59

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1900 1939    3    .04  .12  .11 -.27 -.04  .00 -.11 -.19 -.11 -.13  .13|-.15 -.16  .24* .00  .18  .02 -.19 -.03  .18  .02
    1920 1959   -5   -.25 -.26  .06 -.16  .07  .23* .21  .12  .01  .10  .17|-.16 -.15  .01 -.23  .05 -.13 -.25 -.29 -.39 -.18
    1940 1979    0   -.16 -.17 -.18 -.25 -.14  .07  .07  .08  .12  .26  .28*-.13 -.01 -.22  .04  .04 -.10 -.22 -.24 -.22  .02

 [B] Entire series, effect on correlation (  .401) is:
       Lower   1977> -.028   1952> -.014   1846< -.014   1965< -.013   1926> -.013   2007> -.011  Higher   1857  .017   1874  .017
     1900 to 1939 segment:
       Lower   1906< -.049   1936> -.037   1926> -.036   1916< -.032   1939< -.023   1927> -.020  Higher   1918  .082   1902  .056
     1920 to 1959 segment:
```

```
  Lower   1952> -.065   1941< -.054   1926> -.045   1936> -.037   1939< -.028   1927> -.020  Higher   1956  .067   1959  .064
1940 to 1979 segment:
  Lower   1977> -.126   1965< -.070   1952> -.066   1941< -.049   1970< -.023   1957< -.007  Higher   1976  .061   1956  .051
```

PART 7: DESCRIPTIVE STATISTICS: 11:05 Fri 30 Apr 2010 Page 7

						Corr	//-------- Unfiltered --------\\					//---- Filtered -----\\			
Seq	Series	Interval	No. Years	No. Segmt	No. Flags	with Master	Mean msmt	Max msmt	Std dev	Auto corr	Mean sens	Max value	Std dev	Auto corr	AR ()
1	LC01-1C	1881 2013	133	6	0	.515	1.13	2.90	.629	.858	.233	2.68	.330	-.051	1
2	LC01-2D	1851 2013	163	8	0	.640	1.00	2.04	.369	.835	.162	2.76	.362	.016	1
3	LC01-2E	1840 2012	173	8	0	.568	1.23	4.27	.517	.781	.172	2.66	.388	-.073	2
4	LC01-3C	1905 2013	109	5	0	.510	1.14	3.20	.714	.866	.293	2.80	.409	-.067	1
5	LC01-3D	1823 2013	191	9	3	.396	.72	1.99	.465	.934	.249	2.82	.382	.041	1
6	LC01-4C	1873 2013	141	7	0	.621	.86	2.56	.357	.768	.186	2.75	.403	.008	1
7	LC01-4D	1848 2013	166	8	0	.598	.75	2.19	.276	.707	.200	2.82	.426	.052	1
8	LC01-5B	1843 2012	170	8	0	.496	.74	3.23	.540	.841	.267	2.64	.362	.017	1
9	LC01-5C	1850 2013	164	8	2	.467	.94	3.05	.562	.843	.241	2.70	.414	-.058	2
10	LC01-5D	1886 2013	128	6	1	.506	.80	3.44	.588	.849	.276	2.80	.449	-.012	2
11	LC01-5E	1819 2013	195	10	1	.497	.65	1.55	.302	.790	.238	2.69	.412	.025	1
12	LC01-8A	1815 2012	198	10	1	.524	.78	2.18	.476	.853	.283	2.64	.328	-.047	1
13	LC01-9A	1915 2012	98	5	2	.464	2.26	5.32	1.028	.777	.193	2.83	.466	-.017	3
14	LC01-9B	1939 2012	74	4	0	.481	1.74	4.29	.923	.748	.228	2.95	.558	.027	1
15	LC01-10A	1951 2012	62	3	0	.608	1.82	3.66	.665	.710	.216	2.88	.650	.076	1
16	LC01-10B	1886 2012	127	6	0	.561	.98	2.64	.506	.833	.209	2.63	.371	-.026	2
17	LC01-11A	1896 2012	117	6	2	.524	1.23	3.35	.641	.833	.201	2.73	.417	-.046	1
18	LC01-11B	1875 2012	138	7	1	.546	1.28	4.29	.734	.905	.192	2.80	.449	-.082	1
19	LC01-12A	1883 2012	130	6	2	.580	1.68	6.52	.990	.815	.243	2.97	.459	.029	1
20	LC01-12B	1827 2012	186	9	1	.615	1.22	3.82	.501	.806	.176	2.78	.430	-.006	1
21	LC01-13A	1860 2012	153	7	0	.508	1.61	3.91	.899	.888	.203	2.95	.479	-.035	2
22	LC01-13B	1847 2012	166	8	0	.581	1.43	3.60	.865	.910	.193	2.86	.380	.009	2
23	LC01-14	1838 2012	175	9	0	.438	.86	4.20	.609	.810	.223	2.63	.300	-.002	1
24	LC01-16	1931 2012	82	4	2	.346	1.68	3.89	.814	.821	.220	2.76	.536	.059	1
25	LC01-18A	1874 2012	139	7	2	.412	1.82	5.32	1.126	.929	.218	2.66	.350	.010	1
26	LC01-18B	1870 2012	143	7	1	.501	1.48	3.98	.931	.921	.220	2.70	.415	-.073	1
27	LC01-19A	1904 2012	109	5	0	.586	2.06	4.91	1.007	.890	.196	2.74	.474	-.031	1
28	LC01-19B	1904 2012	109	5	0	.672	2.24	6.47	1.124	.802	.197	2.49	.347	-.014	1
29	LC01-19C	1873 1990	118	6	0	.680	2.04	4.23	.738	.798	.181	2.67	.359	.012	1
30	LC01-19D	1900 2012	113	5	0	.607	1.75	4.20	.787	.847	.213	2.80	.461	.126	1
31	LC01-21A	1863 2012	150	7	1	.430	.70	1.58	.312	.877	.172	2.57	.396	-.092	1
32	LC01-21B	1866 2012	147	7	1	.573	1.15	3.26	.561	.862	.179	2.55	.375	-.052	2
33	LC01-22	1924 2012	89	4	0	.529	1.04	2.54	.382	.676	.184	2.78	.469	-.041	2
34	LC01-23A	1846 2012	167	8	0	.521	1.07	3.75	.553	.850	.177	2.64	.415	-.095	1
35	LC01-24A	1856 2012	157	8	2	.397	.83	1.98	.461	.901	.200	2.78	.395	-.014	2
36	LC01-24B	1845 2008	164	8	2	.405	.67	1.60	.380	.903	.207	2.86	.428	.004	1
37	LC01-25A	1870 2012	143	7	0	.567	1.16	2.61	.480	.844	.155	2.83	.404	-.044	1
38	LC01-25B	1882 2012	131	6	1	.525	1.86	3.98	.804	.859	.172	3.09	.595	.007	1
39	LC01-26A	1879 2011	133	7	2	.423	1.16	4.35	.683	.871	.198	2.49	.334	.007	1

40	LC01-26B	1792 2012	221	10	3	.411	.85	1.94	.379	.841	.172	2.75	.467	.037	1
41	LC01-28A	1822 2012	191	9	0	.596	1.19	2.78	.503	.827	.208	2.85	.379	.047	1
42	LC01-28B	1817 2012	196	10	2	.445	.91	2.43	.479	.893	.198	2.92	.397	.017	1
43	LC01-29A	1850 2012	163	8	0	.573	1.42	3.14	.659	.890	.166	2.73	.506	-.048	1
44	LC01-29B	1816 2012	197	10	0	.591	1.28	3.09	.708	.931	.174	2.67	.351	.001	1
45	LC01-30A	1854 2012	159	8	1	.562	1.22	2.37	.491	.867	.164	2.48	.279	.001	1
46	LC01-31A	1859 2012	154	8	0	.624	.96	2.12	.375	.719	.225	2.55	.294	-.022	1
47	LC01-32A	1844 2012	169	8	0	.531	1.66	3.49	.772	.879	.179	2.75	.395	.002	1
48	LC01-32B	1829 2012	184	9	0	.552	1.62	5.42	1.205	.927	.197	2.79	.434	-.016	1

PART 7: DESCRIPTIVE STATISTICS: 11:05 Fri 30 Apr 2010 Page 8

						Corr	//-------- Unfiltered --------\\					//---- Filtered -----\\			
Seq	Series	Interval	No. Years	No. Segmt	No. Flags	with Master	Mean msmt	Max msmt	Std dev	Auto corr	Mean sens	Max value	Std dev	Auto corr	AR ()
49	LC01-33A	1863 2012	150	7	1	.600	1.54	4.95	.737	.814	.197	2.67	.460	.018	1
50	LC01-34	1894 2012	119	6	1	.500	.70	2.50	.378	.839	.217	2.49	.338	.038	1
51	LC01-35A	1853 2013	161	8	0	.665	1.26	3.17	.703	.898	.165	2.72	.377	-.035	1
52	LC01-35B	1837 2013	177	9	1	.607	1.52	4.10	.773	.905	.158	2.64	.326	.008	1
53	LC01-35C	1858 2012	155	8	0	.615	1.16	4.22	.667	.894	.172	2.77	.341	-.062	2
54	LC01-35D	1834 2012	179	9	0	.753	1.59	4.14	.801	.892	.157	2.80	.370	-.018	2
55	LC01-36B	1877 2012	136	7	1	.488	1.41	4.96	1.132	.928	.308	2.56	.370	.016	1
56	LC01-38A	1830 2012	183	9	3	.415	1.20	3.43	.582	.817	.221	2.76	.398	.006	2
57	LC01-39A	1889 2012	124	6	3	.589	1.07	3.12	.535	.804	.226	2.83	.408	-.048	2
58	LC01-39B	1823 2010	188	9	1	.569	1.40	4.12	.654	.787	.230	2.60	.391	-.009	1
59	LC01-40B	1843 2012	170	8	3	.401	.98	2.19	.495	.904	.174	2.82	.447	-.015	1
Total or mean:			8827	430	50	.534	1.22	6.52	.633	.850	.204	3.09	.402	-.010	

- = [COFECHA TEST COF] = -

Appendix 4. JOLTS outputs (suppression and release) for LC01 chronology

```
[]  Dendroecology Program Library                                             Run SUPP   Program SUP  15:05  Mon 04 Aug 2014  Page   1
[]
[]  SUPPRESSIONS IN TREE GROWTH                                                                              Version 6.01P    29072
-----------------------------------------------------------------------------------------------------------------------------------

 File of tree-ring measurements: good.txt

 Menu of run control parameters:                     Values
 1  Find occurrences of                                  SUP
    by method                                     RUNNING MEAN
                           (Search for SUPPRESSIONS)
 2  RUNNING MEAN SUP factor                            2.000
 3  RUNNING MEAN window                           10 yrs before
                                                   2 yrs after

 RUNNING MEAN method:
       10 years running mean prior to each year tested, and
        2 years running mean starting at each year tested
 4  Min years between reported SUP events         10
 5  ENTIRE TIME SPAN analyzed
 6  Tree age span analyzed                         0       0
 7  File types created                    Out  Sum  Gra  Fhx
 8  Run title:

 Columns of spreadsheet files contain:
  1, 2, 3, 4:     Year, Count of trees, Count of trees recording, Mean tree radius
  5, 6, 7, 8, 9:  Trees in first year of SUP, Mean SUP value, Std dev of SUP value,
                    Mean tree radius at first year of SUP, Percent of trees recording
 10,11,12,13:     Trees in maximum year of SUP, Mean SUP value, Std dev of SUP value, Percent of trees recording
 14,15,16,17:     Trees within SUP, Mean SUP value, Std dev of SUP value, Percent of trees recording

 File SUPP SUP.GRM is in column format

 File SUPP SUP.FHM is in Fire History (FHX2) format
-----------------------------------------------------------------------------------------------------------------------------------
   Series   1   LC01-1C     1881 to  2013   133 years
   ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1909    1909       1    1909   2.115   19.17      29
    1922    1922       1    1922   2.367   24.93      42
    1955    1955       1    1955   2.238   64.73      75
    1977    1977       1    1977   2.040   86.92      97
-----------------------------------------------------------------------------------------------------------------------------------
   Series   2   LC01-2D     1851 to  2013   163 years
        No SUP found in RUNNING MEAN
-----------------------------------------------------------------------------------------------------------------------------------
   Series   3   LC01-2E     1840 to  2012   173 years
```

```
   ____SUP_time_span____     Before/after  Begin_year_SUP Spline_steepest
   Begin     End   Years     Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1952    1952       1     1952   3.538  135.09     113
    1996    1996       1     1996   4.909  184.84     157
-------------------------------------------------------------------------------------------------------------------------------------
   Series   4   LC01-3C      1905 to  2013   109 years
   ____SUP_time_span____     Before/after  Begin_year_SUP Spline_steepest
   Begin     End   Years     Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1931    1931       1     1931   6.552    8.46      27
-------------------------------------------------------------------------------------------------------------------------------------
   Series   5   LC01-3D      1823 to  2013   191 years
   ____SUP_time_span____     Before/after  Begin_year_SUP Spline_steepest
   Begin     End   Years     Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1903    1903       1     1903   2.272   55.23      81
    1934    1934       1     1934  33.003   57.23     112
-------------------------------------------------------------------------------------------------------------------------------------
   Series   6   LC01-4C      1873 to  2013   141 years
   ____SUP_time_span____     Before/after  Begin_year_SUP Spline_steepest
   Begin     End   Years     Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1996    1996       1     1996   2.528  110.08     124
-------------------------------------------------------------------------------------------------------------------------------------
   Series   7   LC01-4D      1848 to  2013   166 years
   ____SUP_time_span____     Before/after  Begin_year_SUP Spline_steepest
   Begin     End   Years     Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1983    1983       1     1983   2.756  103.58     136
-------------------------------------------------------------------------------------------------------------------------------------
   Series   8   LC01-5B      1843 to  2012   170 years
   ____SUP_time_span____     Before/after  Begin_year_SUP Spline_steepest
   Begin     End   Years     Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1918    1918       1     1918   4.841   56.46      76
    1957    1957       1     1957   5.408   78.12     115
    1972    1972       1     1972   3.333   86.22     130
-------------------------------------------------------------------------------------------------------------------------------------
   Series   9   LC01-5C      1850 to  2013   164 years
   ____SUP_time_span____     Before/after  Begin_year_SUP Spline_steepest
   Begin     End   Years     Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1864    1864       1     1864   2.107    9.13      15
    1956    1956       1     1956   8.202   96.17     107
    1967    1967       1     1967   2.056  101.55     118
    1977    1977       1     1977   2.072  107.43     128
-------------------------------------------------------------------------------------------------------------------------------------
   Series  10   LC01-5D      1886 to  2013   128 years
   ____SUP_time_span____     Before/after  Begin_year_SUP Spline_steepest
   Begin     End   Years     Year max_dif  Radius Ring_no    Year   slope
```

```
[] Running mean
   1896    1896       1    1896   2.365    2.30      11
   1914    1914       1    1914   3.815    1.87      29
   1926    1926       1    1926   2.092    8.40      41
   1952    1952       1    1952   2.035   29.98      67
------------------------------------------------------------------------------------------------------------------------------------
  Series  11   LC01-5E     1819 to  2013   195 years
  ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1858    1858       1    1858   2.025   26.77      40
   1918    1918       1    1918   2.045   63.31     100
   1968    1968       1    1968  25.992   88.35     150
------------------------------------------------------------------------------------------------------------------------------------
  Series  12   LC01-8A     1815 to  2012   198 years
  ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1825    1825       1    1825   3.931    1.32      11
   1839    1839       1    1839   3.550    5.11      25
   1908    1908       1    1908   2.506   54.39      94
   1924    1924       1    1924   2.419   58.86     110
------------------------------------------------------------------------------------------------------------------------------------
  Series  13   LC01-9A     1915 to  2012    98 years
  ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1983    1983       1    1983   2.170  172.75      69
   1999    1999       1    1999   2.090  201.24      85
------------------------------------------------------------------------------------------------------------------------------------
  Series  14   LC01-9B     1939 to  2012    74 years
  ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1968    1968       1    1968   2.273   29.70      30
------------------------------------------------------------------------------------------------------------------------------------
  Series  15   LC01-10A    1951 to  2012    62 years
  ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1967    1967       1    1967   2.103   24.41      17
   1998    1998       1    1998   2.123   79.87      48
------------------------------------------------------------------------------------------------------------------------------------
  Series  16   LC01-10B    1886 to  2012   127 years
  ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1947    1947       1    1947   2.137   72.47      62
   1967    1967       1    1967   5.770   83.86      82
   1983    1983       1    1983   2.231   95.10      98
------------------------------------------------------------------------------------------------------------------------------------
```

```
  Series  17   LC01-11A    1896 to  2012   117 years
  ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1906    1906       1    1906   3.750    3.32      11
   1952    1952       1    1952  14.936   49.42      57
-----------------------------------------------------------------------------------------------------------------------------------
  Series  18   LC01-11B    1875 to  2012   138 years
  ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1909    1909       1    1909   2.230   33.71      35
   1924    1924       1    1924 470.103   34.69      50
   1948    1948       1    1948   2.009   59.83      74
-----------------------------------------------------------------------------------------------------------------------------------
  Series  19   LC01-12A    1883 to  2012   130 years
  ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1917    1917       1    1917   2.782   33.36      35
   1955    1955       1    1955   2.266   88.83      73
-----------------------------------------------------------------------------------------------------------------------------------
  Series  20   LC01-12B    1827 to  2012   186 years
  ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1997    1997       1    1997   3.479  204.67     171
-----------------------------------------------------------------------------------------------------------------------------------
  Series  21   LC01-13A    1860 to  2012   153 years
  ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1887    1887       1    1887  37.585   23.93      28
   1918    1918       1    1918   3.253   52.20      59
-----------------------------------------------------------------------------------------------------------------------------------
  Series  22   LC01-13B    1847 to  2012   166 years
  ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1890    1890       1    1890   2.095   46.03      44
   1918    1918       1    1918   4.346   61.08      72
   1952    1952       1    1952   3.431   97.94     106
-----------------------------------------------------------------------------------------------------------------------------------
  Series  23   LC01-14     1838 to  2012   175 years
  ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1923    1923       1    1923   3.838   84.56      86
   1952    1952       1    1952   2.600   98.40     115
   1982    1982       1    1982  29.795  114.67     145
   1992    1992       1    1992   2.231  120.11     155
```

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-----------------------------------------------------------------------------------------------------------------------------------
   Series  24   LC01-16     1931 to  2012    82 years
   ____SUP_time_span____     Before/after  Begin_year_SUP Spline_steepest
   Begin     End   Years     Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1963    1963       1    1963   2.032   56.84      33
    1982    1982       1    1982   2.615   72.11      52
-----------------------------------------------------------------------------------------------------------------------------------
   Series  25   LC01-18A    1874 to  2012   139 years
   ____SUP_time_span____     Before/after  Begin_year_SUP Spline_steepest
   Begin     End   Years     Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1904    1904       1    1904   2.094   32.32      31
    1922    1922       1    1922  32.453   39.15      49
-----------------------------------------------------------------------------------------------------------------------------------
   Series  26   LC01-18B    1870 to  2012   143 years
   ____SUP_time_span____     Before/after  Begin_year_SUP Spline_steepest
   Begin     End   Years     Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1899    1899       1    1899  12.203   17.67      30
    1911    1911       1    1911   2.151   22.39      42
    1955    1955       1    1955   3.932   86.61      86
-----------------------------------------------------------------------------------------------------------------------------------
   Series  27   LC01-19A    1904 to  2012   109 years
   ____SUP_time_span____     Before/after  Begin_year_SUP Spline_steepest
   Begin     End   Years     Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1946    1946       1    1946   2.323   62.37      43
-----------------------------------------------------------------------------------------------------------------------------------
   Series  28   LC01-19B    1904 to  2012   109 years
   ____SUP_time_span____     Before/after  Begin_year_SUP Spline_steepest
   Begin     End   Years     Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    2001    2001       1    2001   2.086  234.64      98
    2011    2011       1    2011   2.631  241.87     108
-----------------------------------------------------------------------------------------------------------------------------------
   Series  29   LC01-19C    1873 to  1990   118 years
        No SUP found in RUNNING MEAN
-----------------------------------------------------------------------------------------------------------------------------------
   Series  30   LC01-19D    1900 to  2012   113 years
   ____SUP_time_span____     Before/after  Begin_year_SUP Spline_steepest
   Begin     End   Years     Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1935    1935       1    1935   2.453   37.00      36
-----------------------------------------------------------------------------------------------------------------------------------
   Series  31   LC01-20     1900 to  2012   113 years
   ____SUP_time_span____     Before/after  Begin_year_SUP Spline_steepest
   Begin     End   Years     Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1997    1997       1    1997   2.381  130.13      98
-----------------------------------------------------------------------------------------------------------------------------------
```

```
  Series  32   LC01-21A    1863 to  2012   150 years
  ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1893    1893       1    1893   2.073   15.28      31
   1973    1973       1    1973   2.324   79.60     111
------------------------------------------------------------------------------------------------------------------------------------
  Series  33   LC01-21B    1866 to  2012   147 years
  ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1971    1971       1    1971   2.256  135.32     106
   1989    1989       1    1989   4.634  144.23     124
------------------------------------------------------------------------------------------------------------------------------------
  Series  34   LC01-22     1924 to  2012    89 years
       No SUP found in RUNNING MEAN
------------------------------------------------------------------------------------------------------------------------------------
  Series  35   LC01-23A    1846 to  2012   167 years
  ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1998    1998       1    1998   2.888  177.30     153
------------------------------------------------------------------------------------------------------------------------------------
  Series  36   LC01-24A    1856 to  2012   157 years
  ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1866    1866       1    1866   3.304    2.63      11
   1907    1907       1    1907   2.250   22.66      52
------------------------------------------------------------------------------------------------------------------------------------
  Series  37   LC01-24B    1845 to  2008   164 years
  ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1866    1866       1    1866   2.202    4.91      22
   1886    1886       1    1886   2.008   10.55      42
------------------------------------------------------------------------------------------------------------------------------------
  Series  38   LC01-25A    1870 to  2012   143 years
  ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1922    1922       1    1922   2.205   48.10      53
   1949    1949       1    1949   2.297   74.09      80
------------------------------------------------------------------------------------------------------------------------------------
  Series  39   LC01-25B    1882 to  2012   131 years
  ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1917    1917       1    1917   2.311   45.35      36
------------------------------------------------------------------------------------------------------------------------------------
  Series  40   LC01-26A    1879 to  2011   133 years
```

```
    ____SUP_time_span____     Before/after  Begin_year_SUP Spline_steepest
    Begin     End   Years     Year max_dif  Radius Ring_no    Year   slope
  [] Running mean
     1909    1909       1     1909   6.694   20.42      31
     1995    1995       1     1995   2.018  122.57     117
-------------------------------------------------------------------------------------------------------------------------------
    Series  41   LC01-26B     1792 to  2012   221 years
    ____SUP_time_span____     Before/after  Begin_year_SUP Spline_steepest
    Begin     End   Years     Year max_dif  Radius Ring_no    Year   slope
  [] Running mean
     1921    1921       1     1921   2.099  113.70     130
     1945    1945       1     1945   2.875  124.51     154
     1994    1994       1     1994   2.735  162.79     203
-------------------------------------------------------------------------------------------------------------------------------
    Series  42   LC01-28A     1822 to  2012   191 years
    ____SUP_time_span____     Before/after  Begin_year_SUP Spline_steepest
    Begin     End   Years     Year max_dif  Radius Ring_no    Year   slope
  [] Running mean
     1836    1836       1     1836   2.455    7.35      15
-------------------------------------------------------------------------------------------------------------------------------
    Series  43   LC01-28B     1817 to  2012   196 years
    ____SUP_time_span____     Before/after  Begin_year_SUP Spline_steepest
    Begin     End   Years     Year max_dif  Radius Ring_no    Year   slope
  [] Running mean
     1834    1834       1     1834   9.739    3.85      18
     1909    1909       1     1909   2.749   56.38      93
     1923    1923       1     1923   2.337   63.61     107
-------------------------------------------------------------------------------------------------------------------------------
    Series  44   LC01-29A     1850 to  2012   163 years
    ____SUP_time_span____     Before/after  Begin_year_SUP Spline_steepest
    Begin     End   Years     Year max_dif  Radius Ring_no    Year   slope
  [] Running mean
     1884    1884       1     1884   2.386   21.80      35
-------------------------------------------------------------------------------------------------------------------------------
    Series  45   LC01-29B     1816 to  2012   197 years
    ____SUP_time_span____     Before/after  Begin_year_SUP Spline_steepest
    Begin     End   Years     Year max_dif  Radius Ring_no    Year   slope
  [] Running mean
     1836    1836       1     1836   2.200   16.97      21
     1864    1864       1     1864   3.466   28.81      49
-------------------------------------------------------------------------------------------------------------------------------
    Series  46   LC01-30A     1854 to  2012   159 years
    ____SUP_time_span____     Before/after  Begin_year_SUP Spline_steepest
    Begin     End   Years     Year max_dif  Radius Ring_no    Year   slope
  [] Running mean
     1886    1886       1     1886   2.271   23.99      33
-------------------------------------------------------------------------------------------------------------------------------
    Series  47   LC01-31A     1859 to  2012   154 years
    ____SUP_time_span____     Before/after  Begin_year_SUP Spline_steepest
    Begin     End   Years     Year max_dif  Radius Ring_no    Year   slope
  [] Running mean
```

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    1998    1998       1    1998   2.122  130.74     140
--------------------------------------------------------------------------------------------------------------------------------------
   Series  48   LC01-32A    1844 to  2012   169 years
   ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1854    1854       1    1854   2.447    3.76      11
--------------------------------------------------------------------------------------------------------------------------------------
   Series  49   LC01-32B    1829 to  2012   184 years
   ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1859    1859       1    1859   2.471    4.62      31
    1895    1895       1    1895  38.925   25.20      67
    1918    1918       1    1918   2.100   53.44      90
--------------------------------------------------------------------------------------------------------------------------------------
   Series  50   LC01-33A    1863 to  2012   150 years
   ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1999    1999       1    1999   2.158  219.11     137
    2009    2009       1    2009   4.794  223.60     147
--------------------------------------------------------------------------------------------------------------------------------------
   Series  51   LC01-34     1894 to  2012   119 years
   ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1971    1971       1    1971   2.132   59.75      78
--------------------------------------------------------------------------------------------------------------------------------------
   Series  52   LC01-35A    1853 to  2013   161 years
   ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1871    1871       1    1871  39.678    2.91      19
    1894    1894       1    1894   2.259   14.65      42
    1910    1910       1    1910   2.203   27.10      58
--------------------------------------------------------------------------------------------------------------------------------------
   Series  53   LC01-35B    1837 to  2013   177 years
   ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1860    1860       1    1860   7.962    3.55      24
    1952    1952       1    1952   2.140  138.53     116
--------------------------------------------------------------------------------------------------------------------------------------
   Series  54   LC01-35C    1858 to  2012   155 years
   ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1876    1876       1    1876  11.658   -1.82      19
--------------------------------------------------------------------------------------------------------------------------------------
   Series  55   LC01-35D    1834 to  2012   179 years
```

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  ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1858    1858       1    1858  40.595    4.79      25
------------------------------------------------------------------------------------------------------------------------------------
  Series  56   LC01-36B    1877 to  2012   136 years
  ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1918    1918       1    1918   2.276   14.95      42
   1954    1954       1    1954  11.850   57.61      78
------------------------------------------------------------------------------------------------------------------------------------
  Series  57   LC01-38A    1830 to  2012   183 years
  ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1950    1950       1    1950   2.798  127.84     121
   1967    1967       1    1967   2.165  140.35     138
------------------------------------------------------------------------------------------------------------------------------------
  Series  58   LC01-39A    1889 to  2012   124 years
  ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1901    1901       1    1901   2.164    5.58      13
   1915    1915       1    1915   2.358   13.02      27
------------------------------------------------------------------------------------------------------------------------------------
  Series  59   LC01-39B    1823 to  2010   188 years
  ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1855    1855       1    1855   2.008   43.77      33
   1917    1917       1    1917   3.327  134.87      95
   1934    1934       1    1934   2.101  153.95     112
   1952    1952       1    1952   2.125  173.96     130
   1968    1968       1    1968   2.185  188.42     146
------------------------------------------------------------------------------------------------------------------------------------
  Series  60   LC01-40B    1843 to  2012   170 years
  ____SUP_time_span____    Before/after  Begin_year_SUP Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1857    1857       1    1857   2.235    4.10      15
   1932    1932       1    1932   7.036   62.10      90
------------------------------------------------------------------------------------------------------------------------------------
        First year of running mean factor is always smaller than prior mean
------------------------------------------------------------------------------------------------------------------------------------
SUMMARY OF SERIES
      60 ring measurement series in file
      60 ring measurement series analyzed

RUNNING MEAN method:
      57 series with SUPs
```

```
     119 SUPs in all trees
   1.983 SUPs per tree, all trees
   2.088 SUPs per tree with SUPs

SUP Summary
    Mean   St Dev
   9.321   43.403 SUP factor, Running mean method

                 - = [ SUPP SUP ] = -
```

```
[]  Dendroecology Program Library                                            Run REL    Program REL  15:08  Mon 04 Aug 2014  Page   1
[]
[]  RELEASES IN TREE GROWTH                                                                                   Version 6.01P    29072
------------------------------------------------------------------------------------------------------------------------------------

 File of tree-ring measurements: good.txt

 Menu of run control parameters:                    Values
 1  Find occurrences of                                 REL
    by method                                     RUNNING MEAN
                            (Search for RELEASES)
 2  RUNNING MEAN REL factor                           2.000
 3  RUNNING MEAN window                           10 yrs before
                                                   2 yrs after

 RUNNING MEAN method:
       10 years running mean prior to each year tested, and
        2 years running mean starting at each year tested
 4  Min years between reported REL events         10
 5  ENTIRE TIME SPAN analyzed
 6  Tree age span analyzed                         0        0
 7  File types created                    Out  Sum  Gra  Fhx
 8  Run title:

 Columns of spreadsheet files contain:
  1, 2, 3, 4:     Year, Count of trees, Count of trees recording, Mean tree radius
  5, 6, 7, 8, 9:  Trees in first year of REL, Mean REL value, Std dev of REL value,
                    Mean tree radius at first year of REL, Percent of trees recording
 10,11,12,13:     Trees in maximum year of REL, Mean REL value, Std dev of REL value, Percent of trees recording
 14,15,16,17:     Trees within REL, Mean REL value, Std dev of REL value, Percent of trees recording

 File REL  REL.GRM is in column format

 File REL  REL.FHM is in Fire History (FHX2) format
------------------------------------------------------------------------------------------------------------------------------------
   Series   1   LC01-1C     1881 to  2013   133 years
   ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1947    1947       1    1947   2.281   90.68      67
    1970    1970       1    1970   2.174  122.97      90
    2005    2005       1    2005   2.092  143.84     125
------------------------------------------------------------------------------------------------------------------------------------
   Series   2   LC01-2D     1851 to  2013   163 years
   ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    2005    2005       1    2005   2.865  155.87     155
------------------------------------------------------------------------------------------------------------------------------------
   Series   3   LC01-2E     1840 to  2012   173 years
   ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
```

```
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1947    1947       1    1947   2.235  131.90     108
   1992    1992       1    1992   2.459  189.55     153
----------------------------------------------------------------------------------------------------------------------------------
  Series   4   LC01-3C     1905 to  2013   109 years
  ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1959    1959       1    1959   2.847   87.54      55
   1992    1992       1    1992   2.007  118.03      88
   2007    2007       1    2007   2.506  123.17     103
----------------------------------------------------------------------------------------------------------------------------------
  Series   5   LC01-3D     1823 to  2013   191 years
  ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1980    1980       1    1980   2.602  129.30     158
   2005    2005       1    2005   2.223  135.75     183
----------------------------------------------------------------------------------------------------------------------------------
  Series   6   LC01-4C     1873 to  2013   141 years
  ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1945    1945       1    1945   2.379   63.76      73
   1986    1986       1    1986   2.036   90.51     114
   2004    2004       1    2004   2.844  108.41     132
----------------------------------------------------------------------------------------------------------------------------------
  Series   7   LC01-4D     1848 to  2013   166 years
  ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1905    1905       1    1905   2.512   40.37      58
   1975    1975       1    1975   2.518   90.30     128
   2005    2005       1    2005   2.498  115.79     158
----------------------------------------------------------------------------------------------------------------------------------
  Series   8   LC01-5B     1843 to  2012   170 years
  ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1887    1887       1    1887   2.110   24.85      45
   1944    1944       1    1944   4.715   74.58     102
   1962    1962       1    1962   2.721   94.03     120
   1992    1992       1    1992   2.606  115.26     150
----------------------------------------------------------------------------------------------------------------------------------
  Series   9   LC01-5C     1850 to  2013   164 years
  ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1877    1877       1    1877   2.115   24.86      28
   1907    1907       1    1907   2.019   47.12      58
```

```
   1943    1943       1    1943   4.950   80.44      94
   1962    1962       1    1962   2.180  111.85     113
------------------------------------------------------------------------------------------------------------------------------------
  Series  10   LC01-5D     1886 to  2013   128 years
  ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1943    1943       1    1943   2.149   67.42      58
   1966    1966       1    1966   2.678   81.84      81
   1992    1992       1    1992   2.362   92.25     107
   2005    2005       1    2005   2.087   97.16     120
------------------------------------------------------------------------------------------------------------------------------------
  Series  11   LC01-5E     1819 to  2013   195 years
       No REL found in RUNNING MEAN
------------------------------------------------------------------------------------------------------------------------------------
  Series  12   LC01-8A     1815 to  2012   198 years
  ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1880    1880       1    1880   2.207   65.19      66
   1901    1901       1    1901   2.810   81.04      87
   1959    1959       1    1959   2.124  135.92     145
   1982    1982       1    1982   2.081  145.91     168
   2008    2008       1    2008   2.796  153.65     194
------------------------------------------------------------------------------------------------------------------------------------
  Series  13   LC01-9A     1915 to  2012    98 years
       No REL found in RUNNING MEAN
------------------------------------------------------------------------------------------------------------------------------------
  Series  14   LC01-9B     1939 to  2012    74 years
  ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1996    1996       1    1996   2.311  101.31      58
   2006    2006       1    2006   2.030  120.17      68
------------------------------------------------------------------------------------------------------------------------------------
  Series  15   LC01-10A    1951 to  2012    62 years
       No REL found in RUNNING MEAN
------------------------------------------------------------------------------------------------------------------------------------
  Series  16   LC01-10B    1886 to  2012   127 years
  ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1958    1958       1    1958   2.278   59.89      73
   2005    2005       1    2005   2.844  114.73     120
------------------------------------------------------------------------------------------------------------------------------------
  Series  17   LC01-11A    1896 to  2012   117 years
  ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1994    1994       1    1994   2.103  123.84      99
------------------------------------------------------------------------------------------------------------------------------------
```

```
   Series  18   LC01-11B    1875 to  2012   138 years
   ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1902    1902       1    1902   2.137   40.40      28
    1992    1992       1    1992   2.277  161.33     118
-------------------------------------------------------------------------------------------------------------------------------------
   Series  19   LC01-12A    1883 to  2012   130 years
   ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1901    1901       1    1901   2.520   31.23      19
    1992    1992       1    1992   2.479  196.81     110
-------------------------------------------------------------------------------------------------------------------------------------
   Series  20   LC01-12B    1827 to  2012   186 years
   ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1986    1986       1    1986   2.168  189.70     160
-------------------------------------------------------------------------------------------------------------------------------------
   Series  21   LC01-13A    1860 to  2012   153 years
        No REL found in RUNNING MEAN
-------------------------------------------------------------------------------------------------------------------------------------
   Series  22   LC01-13B    1847 to  2012   166 years
   ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1938    1938       1    1938   2.154  173.58      92
    1963    1963       1    1963   2.185  211.26     117
    2006    2006       1    2006   2.824  232.33     160
-------------------------------------------------------------------------------------------------------------------------------------
   Series  23   LC01-14     1838 to  2012   175 years
   ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1968    1968       1    1968   2.073  109.83     131
    1989    1989       1    1989   2.068  143.06     152
-------------------------------------------------------------------------------------------------------------------------------------
   Series  24   LC01-16     1931 to  2012    82 years
        No REL found in RUNNING MEAN
-------------------------------------------------------------------------------------------------------------------------------------
   Series  25   LC01-18A    1874 to  2012   139 years
   ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1990    1990       1    1990   2.258  212.01     117
-------------------------------------------------------------------------------------------------------------------------------------
   Series  26   LC01-18B    1870 to  2012   143 years
   ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
```

```
    1992    1992       1    1992   2.029  197.70     123
------------------------------------------------------------------------------------------------------------------------------------
   Series  27   LC01-19A    1904 to  2012   109 years
        No REL found in RUNNING MEAN
------------------------------------------------------------------------------------------------------------------------------------
   Series  28   LC01-19B    1904 to  2012   109 years
   ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1994    1994       1    1994   2.187  171.49      91
------------------------------------------------------------------------------------------------------------------------------------
   Series  29   LC01-19C    1873 to  1990   118 years
        No REL found in RUNNING MEAN
------------------------------------------------------------------------------------------------------------------------------------
   Series  30   LC01-19D    1900 to  2012   113 years
   ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1986    1986       1    1986   2.653  163.47      87
    2005    2005       1    2005   2.601  182.98     106
------------------------------------------------------------------------------------------------------------------------------------
   Series  31   LC01-20     1900 to  2012   113 years
   ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1990    1990       1    1990   2.097  123.64      91
    2005    2005       1    2005   2.003  146.85     106
------------------------------------------------------------------------------------------------------------------------------------
   Series  32   LC01-21A    1863 to  2012   150 years
   ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1960    1960       1    1960   2.040   61.11      98
------------------------------------------------------------------------------------------------------------------------------------
   Series  33   LC01-21B    1866 to  2012   147 years
   ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1959    1959       1    1959   2.437   84.62      94
------------------------------------------------------------------------------------------------------------------------------------
   Series  34   LC01-22     1924 to  2012    89 years
   ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    2004    2004       1    2004   2.703   79.64      81
------------------------------------------------------------------------------------------------------------------------------------
   Series  35   LC01-23A    1846 to  2012   167 years
   ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1985    1985       1    1985   2.469  128.07     140
```

```
    2005    2005       1    2005   2.109  161.08     160
------------------------------------------------------------------------------------------------------------------------------------
   Series  36   LC01-24A    1856 to  2012   157 years
        No REL found in RUNNING MEAN
------------------------------------------------------------------------------------------------------------------------------------
   Series  37   LC01-24B    1845 to  2008   164 years
   ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1919    1919       1    1919   2.133   66.46      75
    2005    2005       1    2005   2.823  109.11     161
------------------------------------------------------------------------------------------------------------------------------------
   Series  38   LC01-25A    1870 to  2012   143 years
        No REL found in RUNNING MEAN
------------------------------------------------------------------------------------------------------------------------------------
   Series  39   LC01-25B    1882 to  2012   131 years
   ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    2005    2005       1    2005   2.505  234.01     124
------------------------------------------------------------------------------------------------------------------------------------
   Series  40   LC01-26A    1879 to  2011   133 years
   ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1989    1989       1    1989   2.101  132.81     111
------------------------------------------------------------------------------------------------------------------------------------
   Series  41   LC01-26B    1792 to  2012   221 years
   ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1985    1985       1    1985   2.261  171.46     194
------------------------------------------------------------------------------------------------------------------------------------
   Series  42   LC01-28A    1822 to  2012   191 years
   ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1980    1980       1    1980   2.263  209.54     159
    2005    2005       1    2005   2.555  221.53     184
------------------------------------------------------------------------------------------------------------------------------------
   Series  43   LC01-28B    1817 to  2012   196 years
   ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    2004    2004       1    2004   2.825  172.24     188
------------------------------------------------------------------------------------------------------------------------------------
   Series  44   LC01-29A    1850 to  2012   163 years
        No REL found in RUNNING MEAN
------------------------------------------------------------------------------------------------------------------------------------
   Series  45   LC01-29B    1816 to  2012   197 years
   ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
```

```
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   2009    2009       1    2009   2.228  251.22     194
------------------------------------------------------------------------------------------------------------------------------------
  Series  46   LC01-30A    1854 to  2012   159 years
  ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1949    1949       1    1949   2.319  135.31      96
------------------------------------------------------------------------------------------------------------------------------------
  Series  47   LC01-31A    1859 to  2012   154 years
  ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1986    1986       1    1986   2.070  125.65     128
------------------------------------------------------------------------------------------------------------------------------------
  Series  48   LC01-32A    1844 to  2012   169 years
  ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1959    1959       1    1959   2.172  221.26     116
   1975    1975       1    1975   2.342  237.73     132
   1995    1995       1    1995   2.017  259.45     152
------------------------------------------------------------------------------------------------------------------------------------
  Series  49   LC01-32B    1829 to  2012   184 years
  ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1975    1975       1    1975   2.353  278.88     147
------------------------------------------------------------------------------------------------------------------------------------
  Series  50   LC01-33A    1863 to  2012   150 years
  ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1975    1975       1    1975   2.047  165.97     113
   2003    2003       1    2003   2.110  208.83     141
------------------------------------------------------------------------------------------------------------------------------------
  Series  51   LC01-34     1894 to  2012   119 years
  ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   2005    2005       1    2005   3.096   71.39     112
------------------------------------------------------------------------------------------------------------------------------------
  Series  52   LC01-35A    1853 to  2013   161 years
       No REL found in RUNNING MEAN
------------------------------------------------------------------------------------------------------------------------------------
  Series  53   LC01-35B    1837 to  2013   177 years
  ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
  Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
[] Running mean
   1941    1941       1    1941   2.220  191.24     105
```

```
-----------------------------------------------------------------------------------------------------------------------------------
   Series  54   LC01-35C    1858 to  2012   155 years
   ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1942    1942       1    1942   2.002  127.77      85
-----------------------------------------------------------------------------------------------------------------------------------
   Series  55   LC01-35D    1834 to  2012   179 years
   ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1941    1941       1    1941   2.045  203.24     108
-----------------------------------------------------------------------------------------------------------------------------------
   Series  56   LC01-36B    1877 to  2012   136 years
   ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1941    1941       1    1941   2.365  129.15      65
    1986    1986       1    1986   2.170  182.47     110
-----------------------------------------------------------------------------------------------------------------------------------
   Series  57   LC01-38A    1830 to  2012   183 years
   ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1906    1906       1    1906   2.955   92.86      77
    1960    1960       1    1960   2.642  176.85     131
-----------------------------------------------------------------------------------------------------------------------------------
   Series  58   LC01-39A    1889 to  2012   124 years
        No REL found in RUNNING MEAN
-----------------------------------------------------------------------------------------------------------------------------------
   Series  59   LC01-39B    1823 to  2010   188 years
   ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1911    1911       1    1911   2.475  115.61      89
    2005    2005       1    2005   2.219  256.34     183
-----------------------------------------------------------------------------------------------------------------------------------
   Series  60   LC01-40B    1843 to  2012   170 years
   ____REL_time_span____    Before/after  Begin_year_REL Spline_steepest
   Begin     End   Years    Year max_dif  Radius Ring_no    Year   slope
 [] Running mean
    1975    1975       1    1975   2.413  148.45     133
-----------------------------------------------------------------------------------------------------------------------------------
        First year of running mean factor is always smaller than prior mean
-----------------------------------------------------------------------------------------------------------------------------------
 SUMMARY OF SERIES
       60 ring measurement series in file
       60 ring measurement series analyzed

 RUNNING MEAN method:
       48 series with RELs
```

```
      89 RELs in all trees
   1.483 RELs per tree, all trees
   1.854 RELs per tree with RELs

REL Summary
    Mean   St Dev
   2.399     .461 REL factor, Running mean method

                 - = [ REL  REL ] = -
```

Appendix 5. OUTBREAK Outputs (Run with Clingman's Dome Chronology and LCR Reference)

```
[]  Dendroecology Program Library                                          Run CLING  Program OBR  14:08  Thu 17 Jul 2014  Page   1
[]
[]  BUDWORM, TUSSOCK, PANDORA OUTBREAK DETECTION                                                             Version 6.00P    29054
------------------------------------------------------------------------------------------------------------------------------------

 CONTROL CHRONOLOGY (non-host species):  nc002_crn.txt
 HOST TREE indices or chronologies:      goodlinearstd.txt
 Title of run:

 Menu options:                                 Selected values
 -------------                                 ---------------
 Names of insects (Symbols)               BUDWORM (B,b)  TUSSOCK (T,t)

 Maximum growth reduction threshold
   1  BUDWORM                                   -1.28 Std Dev
   2  TUSSOCK                                   -1.28 Std Dev
 Minimum number of years for outbreak
   3  BUDWORM                                       8
         Outbreak omitted if it does not attain   8 years at end of series
   4  TUSSOCK                                       3
         Outbreak omitted if it does not attain   3 years at end of series
 Maximum years to count in outbreak
   5  TUSSOCK                                       4

   6  Rate of increase in growth reduction to
      identify TUSSOCK outbreaks                  1.000

   7  File made for plotting with Program PAGEPLOT:      N
      overlaying control chronology and uncorrected experimental series;
      and experimental series before and after correction

   8  File of negative corrected indices                N


   9  Control chronology indices unchanged

 New files are:

      CLINGOBR.OUT  For printing
      CLINGOBR.COR  Tree indices corrected, Measurement format
      CLINGOBR.MNC  Mean of corrected tree indices, Measurement format
      CLINGOBR.NOR  Tree indices corrected and normalized, Compact format
      CLINGOBR.DIF  Differences, uncorrected minus corrected series, Compact format
      CLINGOBR.COL  Data in tab-delimited columns:  year, no of trees; count of outbreaks, percent of trees infested and maxima
                      for BUDWORM and TUSSOCK; corrected mean indices; corrected normalized indices
       and OBR.CRN  Mean chronology in publication format, appended

 Text in file: good -- no data title --                                  1st itrdb line missing
```

```
Text in file: good -- no data title --                                  2nd itrdb line missing
Text in file: good -- no data title --                                  3rd itrdb line missing
Text in file: STNDRD 1 CLINGMAN'S DOME              - STANDARD           PCRU
Text in file: STNDRD 2 N. CAROLINA  RED SPRUCE              3536-08326         1558 1983
Text in file: STNDRD 3 ED COOK

Control chronology:   STNDRD    1558  1983   426 years
Experimental series    1 trees  1792  2013   222 years
Analyzed time span              1792  1983   192 years
==================================================================================================================================
STATISTICS FOR CONTROL CHRONOLOGY AND EXPERIMENTAL SERIES BEFORE AND AFTER CORRECTION
Text in file: good -- no data title --                                  1st itrdb line missing
Text in file: good -- no data title --                                  2nd itrdb line missing
Text in file: good -- no data title --                                  3rd itrdb line missing

                                               Mean    Std   Skew- Kurto-  Trend   Partial autocorr  L-Box    Corr/  STATISTICS   1
Seq  Series     Interval  Years  Mean  Median   sens    dev   ness    sis  var %  Ord 1 Ord 2 Ord 3   Prob    Cntrl
---  --------  ---------- -----  ----- ------  -----  -----  ----- ------ ------- ----- ----- -----  -----    -----

     Control   1792  1983   192  1.011   .979   .124   .224   .424  -.396   .0360   .71   .07  -.05   .000
  1  good_r    1792  1983   192   .980   .955   .118   .180   .874  1.572   .0240   .62   .00   .05   .000     .258
     Correct   1792  1983   192  1.000   .974   .116   .219   .385   .250   .0184   .75  -.09   .04   .000    -.609

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
MEAN SERIES                                    Mean    Std   Skew- Kurto-  Trend   Partial autocorr  L-Box    Corr/ STATISTICS MEAN
     Series     Interval  Years  Mean  Median   sens    dev   ness    sis  var %  Ord 1 Ord 2 Ord 3   Prob    Cntrl
     --------  ---------- -----  ----- ------  -----  -----  ----- ------ ------- ----- ----- -----  -----    -----
     Control   1792  1983   192  1.011   .979   .124   .224   .424  -.396   .0360   .71   .07  -.05   .000    -.609
     TreeMean  1792  1983   192   .980   .955   .118   .180   .874  1.572   .0240   .62   .00   .05   .000     .258
     Correct   1792  1983   192  1.000   .974   .116   .219   .385   .250   .0184   .75  -.09   .04   .000    -.609

==================================================================================================================================
OUTBREAKS by SERIES
----------------------------------------------------------------------------------------------------------------------------------
TREE good_r    Span  1792  1983   192 years                                                                            SERIES   1
          Outbreak   No_of    _____Max_Growth_Reduction______    Mean_periodic   Max_rate_G.R.
Insect   time__span  Years   Year   Depart  CrIndex  Percent  growth_reduction  Year   Change
BUDWORM  1814  1841    28    1820   -1.750     .598   38.24%        13.97%       1811     1.94
BUDWORM  1955  1968    14    1968   -1.739     .600   38.02%        21.41%       1967     1.13
BUDWORM  1971  1983    13    1974   -1.669     .615   36.49%        20.19%       1971     1.23
TUSSOCK  1792  1795     4    1795   -2.253     .487   49.26%        35.62%       1792     1.23
TUSSOCK  1885  1888     4    1888   -2.141     .512   46.79%        27.94%       1887     1.04
TUSSOCK  1955  1958     4    1957   -1.538     .644   33.61%        23.53%       1957      .75
                                                           (Omitted: increase in growth reduction is below threshold)
TUSSOCK  1971  1974     4    1974   -1.669     .615   36.49%        22.92%       1971     1.23
--------------------------------
TREE good_r    OUTBREAKS by YEAR
Decade  0         1         2         3         4         5         6         7         8         9
    Year 0123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123456789

   1700                                                                                         ........
```

```
   1700                                                                                              tttT....
   1800  ..............bbbbbbBbbbbbbbbbbbbbbbbbbbbb..........................................................
   1800  .....................................................................................tttT...........
   1900  .......................................................bbbbbbbbbbbbbB..bbbBbbbbbbbbb
   1900  .......................................................................tttT.........
-------------------------------------------------------------------------------------------------------------------------------
MEAN SERIES CLING Mn  Span  1792  1983   192 years                                                                 MEAN SERIES
          Outbreak   No_of    _____Max_Growth_Reduction______    Mean_periodic   Max_rate_G.R.
Insect   time__span  Years   Year   Depart  CrIndex  Percent  growth_reduction  Year   Change
BUDWORM  1814  1841    28    1820   -1.750     .598   38.24%       13.97%       1811     1.94
BUDWORM  1955  1968    14    1968   -1.739     .600   38.02%       21.41%       1967     1.13
BUDWORM  1971  1983    13    1974   -1.669     .615   36.49%       20.19%       1971     1.23
TUSSOCK  1792  1795     4    1795   -2.253     .487   49.26%       35.62%       1792     1.23
TUSSOCK  1885  1888     4    1888   -2.141     .512   46.79%       27.94%       1887     1.04
TUSSOCK  1955  1958     4    1957   -1.538     .644   33.61%       23.53%       1957      .75
                                                           (Omitted: increase in growth reduction is below threshold)
TUSSOCK  1971  1974     4    1974   -1.669     .615   36.49%       22.92%       1971     1.23
--------------------------------
TREE CLING Mn  OUTBREAKS by YEAR
Decade   0         1         2         3         4         5         6         7         8         9
    Year 0123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123456789

   1700                                                                                              ........
   1700                                                                                              tttT....
   1800  ..............bbbbbbBbbbbbbbbbbbbbbbbbbbbb..........................................................
   1800  .....................................................................................tttT...........
   1900  .......................................................bbbbbbbbbbbbbB..bbbBbbbbbbbbb
   1900  .......................................................................tttT.........

===================================================================================================================================

YEAR-BY-YEAR LIST of DEPARTURES (ST DEVS) and COUNTS
------------------------------------------------------------------------------------------------------------------------ DECADE 1792
    Ident       1792      1793      1794      1795      1796      1797      1798      1799      1800      1801
               -----     -----     -----     -----     -----     -----     -----     -----     -----     -----

    good_r     -1.23 t   -1.38 t   -1.66 t   -2.25 T    -.40      2.05       .26       .38       .24      -.15
    CLING Mn   -1.23 t   -1.38 t   -1.66 t   -2.25 T    -.40      2.05       .26       .38       .24      -.15

N of TREES         1         1         1         1         1         1         1         1         1         1
BUDWORM ct         0         0         0         0         0         0         0         0         0         0
BUDWORM mx         0         0         0         0         0         0         0         0         0         0
TUSSOCK ct         1         1         1         1         0         0         0         0         0         0
TUSSOCK mx         0         0         0         1         0         0         0         0         0         0
------------------------------------------------------------------------------------------------------------------------ DECADE 1802
    Ident       1802      1803      1804      1805      1806      1807      1808      1809      1810      1811
               -----     -----     -----     -----     -----     -----     -----     -----     -----     -----

    good_r       .39      -.31       .26     -1.34      -.53       .17      2.26      3.37      1.48      -.46
    CLING Mn     .39      -.31       .26     -1.34      -.53       .17      2.26      3.37      1.48      -.46

N of TREES         1         1         1         1         1         1         1         1         1         1
BUDWORM ct         0         0         0         0         0         0         0         0         0         0
```

```
BUDWORM mx        0          0          0          0          0          0          0          0          0          0
TUSSOCK ct        0          0          0          0          0          0          0          0          0          0
TUSSOCK mx        0          0          0          0          0          0          0          0          0          0
------------------------------------------------------------------------------------------------------------------------ DECADE 1812
    Ident       1812       1813       1814       1815       1816       1817       1818       1819       1820       1821
               -----      -----      -----      -----      -----      -----      -----      -----      -----      -----
    good_r      -.57        .24      -.28b       .82b      -.07b      -.48b      -.88b     -1.20b     -1.75B     -1.38b
    CLING Mn    -.57        .24      -.28b       .82b      -.07b      -.48b      -.88b     -1.20b     -1.75B     -1.38b

N of TREES        1          1          1          1          1          1          1          1          1          1
BUDWORM ct        0          0          1          1          1          1          1          1          1          1
BUDWORM mx        0          0          0          0          0          0          0          0          1          0
TUSSOCK ct        0          0          0          0          0          0          0          0          0          0
TUSSOCK mx        0          0          0          0          0          0          0          0          0          0
------------------------------------------------------------------------------------------------------------------------ DECADE 1822
    Ident       1822       1823       1824       1825       1826       1827       1828       1829       1830       1831
               -----      -----      -----      -----      -----      -----      -----      -----      -----      -----
    good_r      -.88b      -.48b      -.40b      -.40b      -.77b      -.44b      -.21b      -.87b     -1.21b      -.98b
    CLING Mn    -.88b      -.48b      -.40b      -.40b      -.77b      -.44b      -.21b      -.87b     -1.21b      -.98b

N of TREES        1          1          1          1          1          1          1          1          1          1
BUDWORM ct        1          1          1          1          1          1          1          1          1          1
BUDWORM mx        0          0          0          0          0          0          0          0          0          0
TUSSOCK ct        0          0          0          0          0          0          0          0          0          0
TUSSOCK mx        0          0          0          0          0          0          0          0          0          0
------------------------------------------------------------------------------------------------------------------------ DECADE 1832
    Ident       1832       1833       1834       1835       1836       1837       1838       1839       1840       1841
               -----      -----      -----      -----      -----      -----      -----      -----      -----      -----
    good_r      -.15b     -1.57b     -1.50b     -1.15b     -1.30b      -.26b      -.33b       .52b      -.24b      -.05b
    CLING Mn    -.15b     -1.57b     -1.50b     -1.15b     -1.30b      -.26b      -.33b       .52b      -.24b      -.05b

N of TREES        1          1          1          1          1          1          1          1          1          1
BUDWORM ct        1          1          1          1          1          1          1          1          1          1
BUDWORM mx        0          0          0          0          0          0          0          0          0          0
TUSSOCK ct        0          0          0          0          0          0          0          0          0          0
TUSSOCK mx        0          0          0          0          0          0          0          0          0          0
------------------------------------------------------------------------------------------------------------------------ DECADE 1842
    Ident       1842       1843       1844       1845       1846       1847       1848       1849       1850       1851
               -----      -----      -----      -----      -----      -----      -----      -----      -----      -----
    good_r       .49        .59        .89        .66        .82        .19       -.28       -.15       -.62       -.60
    CLING Mn     .49        .59        .89        .66        .82        .19       -.28       -.15       -.62       -.60

N of TREES        1          1          1          1          1          1          1          1          1          1
BUDWORM ct        0          0          0          0          0          0          0          0          0          0
BUDWORM mx        0          0          0          0          0          0          0          0          0          0
TUSSOCK ct        0          0          0          0          0          0          0          0          0          0
TUSSOCK mx        0          0          0          0          0          0          0          0          0          0
------------------------------------------------------------------------------------------------------------------------ DECADE 1852
    Ident       1852       1853       1854       1855       1856       1857       1858       1859       1860       1861
               -----      -----      -----      -----      -----      -----      -----      -----      -----      -----
    good_r      -.48       -.24       -.69       -.33       1.28       1.00       1.10        .87        .61        .67
```

CLING Mn	-.48	-.24	-.69	-.33	1.28	1.00	1.10	.87	.61	.67
N of TREES	1	1	1	1	1	1	1	1	1	1
BUDWORM ct	0	0	0	0	0	0	0	0	0	0
BUDWORM mx	0	0	0	0	0	0	0	0	0	0
TUSSOCK ct	0	0	0	0	0	0	0	0	0	0
TUSSOCK mx	0	0	0	0	0	0	0	0	0	0

DECADE 1862

Ident	1862	1863	1864	1865	1866	1867	1868	1869	1870	1871
good_r	1.06	.70	-.12	.16	.43	.27	.63	1.10	.98	.30
CLING Mn	1.06	.70	-.12	.16	.43	.27	.63	1.10	.98	.30
N of TREES	1	1	1	1	1	1	1	1	1	1
BUDWORM ct	0	0	0	0	0	0	0	0	0	0
BUDWORM mx	0	0	0	0	0	0	0	0	0	0
TUSSOCK ct	0	0	0	0	0	0	0	0	0	0
TUSSOCK mx	0	0	0	0	0	0	0	0	0	0

DECADE 1872

Ident	1872	1873	1874	1875	1876	1877	1878	1879	1880	1881
good_r	.43	.44	-.28	-.25	.04	-.23	-.33	-.83	-.31	-.02
CLING Mn	.43	.44	-.28	-.25	.04	-.23	-.33	-.83	-.31	-.02
N of TREES	1	1	1	1	1	1	1	1	1	1
BUDWORM ct	0	0	0	0	0	0	0	0	0	0
BUDWORM mx	0	0	0	0	0	0	0	0	0	0
TUSSOCK ct	0	0	0	0	0	0	0	0	0	0
TUSSOCK mx	0	0	0	0	0	0	0	0	0	0

DECADE 1882

Ident	1882	1883	1884	1885	1886	1887	1888	1889	1890	1891
good_r	.06	.43	.09	-.83 t	-.55 t	-1.59 t	-2.14 T	-1.61	-1.53	.12
CLING Mn	.06	.43	.09	-.83 t	-.55 t	-1.59 t	-2.14 T	-1.61	-1.53	.12
N of TREES	1	1	1	1	1	1	1	1	1	1
BUDWORM ct	0	0	0	0	0	0	0	0	0	0
BUDWORM mx	0	0	0	0	0	0	0	0	0	0
TUSSOCK ct	0	0	0	1	1	1	1	0	0	0
TUSSOCK mx	0	0	0	0	0	0	1	0	0	0

DECADE 1892

Ident	1892	1893	1894	1895	1896	1897	1898	1899	1900	1901
good_r	.50	.42	-.35	-.85	-.65	-.86	.11	.95	1.30	1.25
CLING Mn	.50	.42	-.35	-.85	-.65	-.86	.11	.95	1.30	1.25
N of TREES	1	1	1	1	1	1	1	1	1	1
BUDWORM ct	0	0	0	0	0	0	0	0	0	0
BUDWORM mx	0	0	0	0	0	0	0	0	0	0
TUSSOCK ct	0	0	0	0	0	0	0	0	0	0
TUSSOCK mx	0	0	0	0	0	0	0	0	0	0

DECADE 1902

Ident	1902	1903	1904	1905	1906	1907	1908	1909	1910	1911
good_r	2.33	1.53	1.47	.82	2.16	.99	.85	.04	-.28	.84
CLING Mn	2.33	1.53	1.47	.82	2.16	.99	.85	.04	-.28	.84
N of TREES	1	1	1	1	1	1	1	1	1	1
BUDWORM ct	0	0	0	0	0	0	0	0	0	0
BUDWORM mx	0	0	0	0	0	0	0	0	0	0
TUSSOCK ct	0	0	0	0	0	0	0	0	0	0
TUSSOCK mx	0	0	0	0	0	0	0	0	0	0

DECADE 1912

Ident	1912	1913	1914	1915	1916	1917	1918	1919	1920	1921
good_r	.74	.52	2.11	1.32	1.52	.33	-.01	-.47	-.18	.03
CLING Mn	.74	.52	2.11	1.32	1.52	.33	-.01	-.47	-.18	.03
N of TREES	1	1	1	1	1	1	1	1	1	1
BUDWORM ct	0	0	0	0	0	0	0	0	0	0
BUDWORM mx	0	0	0	0	0	0	0	0	0	0
TUSSOCK ct	0	0	0	0	0	0	0	0	0	0
TUSSOCK mx	0	0	0	0	0	0	0	0	0	0

DECADE 1922

Ident	1922	1923	1924	1925	1926	1927	1928	1929	1930	1931
good_r	-.31	-.52	.05	-.15	.10	.08	-.28	-.10	.20	.06
CLING Mn	-.31	-.52	.05	-.15	.10	.08	-.28	-.10	.20	.06
N of TREES	1	1	1	1	1	1	1	1	1	1
BUDWORM ct	0	0	0	0	0	0	0	0	0	0
BUDWORM mx	0	0	0	0	0	0	0	0	0	0
TUSSOCK ct	0	0	0	0	0	0	0	0	0	0
TUSSOCK mx	0	0	0	0	0	0	0	0	0	0

DECADE 1932

Ident	1932	1933	1934	1935	1936	1937	1938	1939	1940	1941
good_r	-.53	-.11	-.24	-.24	.00	1.35	1.46	.99	.85	1.79
CLING Mn	-.53	-.11	-.24	-.24	.00	1.35	1.46	.99	.85	1.79
N of TREES	1	1	1	1	1	1	1	1	1	1
BUDWORM ct	0	0	0	0	0	0	0	0	0	0
BUDWORM mx	0	0	0	0	0	0	0	0	0	0
TUSSOCK ct	0	0	0	0	0	0	0	0	0	0
TUSSOCK mx	0	0	0	0	0	0	0	0	0	0

DECADE 1942

Ident	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951
good_r	1.26	.74	1.01	1.08	1.82	1.61	1.55	1.65	1.27	2.84
CLING Mn	1.26	.74	1.01	1.08	1.82	1.61	1.55	1.65	1.27	2.84
N of TREES	1	1	1	1	1	1	1	1	1	1

```
BUDWORM ct         0         0         0         0         0         0         0         0         0         0
BUDWORM mx         0         0         0         0         0         0         0         0         0         0
TUSSOCK ct         0         0         0         0         0         0         0         0         0         0
TUSSOCK mx         0         0         0         0         0         0         0         0         0         0
------------------------------------------------------------------------------------------------------------------------ DECADE 1952
    Ident       1952      1953      1954      1955      1956      1957      1958      1959      1960      1961
               -----     -----     -----     -----     -----     -----     -----     -----     -----     -----
    good_r      1.28       .25       .26      -.46b     -.79b    -1.54b    -1.52b     -.58b    -1.04b    -1.46b
    CLING Mn    1.28       .25       .26      -.46b     -.79b    -1.54b    -1.52b     -.58b    -1.04b    -1.46b

N of TREES         1         1         1         1         1         1         1         1         1         1
BUDWORM ct         0         0         0         1         1         1         1         1         1         1
BUDWORM mx         0         0         0         0         0         0         0         0         0         0
TUSSOCK ct         0         0         0         0         0         0         0         0         0         0
TUSSOCK mx         0         0         0         0         0         0         0         0         0         0
------------------------------------------------------------------------------------------------------------------------ DECADE 1962
    Ident       1962      1963      1964      1965      1966      1967      1968      1969      1970      1971
               -----     -----     -----     -----     -----     -----     -----     -----     -----     -----
    good_r      -.84b     -.67b     -.78b     -.15b     -.51b    -1.64b    -1.74B      .22       .63      -.60bt
    CLING Mn    -.84b     -.67b     -.78b     -.15b     -.51b    -1.64b    -1.74B      .22       .63      -.60bt

N of TREES         1         1         1         1         1         1         1         1         1         1
BUDWORM ct         1         1         1         1         1         1         1         0         0         1
BUDWORM mx         0         0         0         0         0         0         1         0         0         0
TUSSOCK ct         0         0         0         0         0         0         0         0         0         1
TUSSOCK mx         0         0         0         0         0         0         0         0         0         0
------------------------------------------------------------------------------------------------------------------------ DECADE 1972
    Ident       1972      1973      1974      1975      1976      1977      1978      1979      1980      1981
               -----     -----     -----     -----     -----     -----     -----     -----     -----     -----
    good_r      -.79bt   -1.13bt   -1.67BT   -1.66b    -1.27b    -1.32b    -1.59b    -1.02b     -.25b      .45b
    CLING Mn    -.79bt   -1.13bt   -1.67BT   -1.66b    -1.27b    -1.32b    -1.59b    -1.02b     -.25b      .45b

N of TREES         1         1         1         1         1         1         1         1         1         1
BUDWORM ct         1         1         1         1         1         1         1         1         1         1
BUDWORM mx         0         0         1         0         0         0         0         0         0         0
TUSSOCK ct         1         1         1         0         0         0         0         0         0         0
TUSSOCK mx         0         0         1         0         0         0         0         0         0         0
------------------------------------------------------------------------------------------------------------------------ DECADE 1982
    Ident       1982      1983
               -----     -----     -----     -----     -----     -----     -----     -----     -----     -----
    good_r      -.29b     -.87b
    CLING Mn    -.29b     -.87b

N of TREES         1         1
BUDWORM ct         1         1
BUDWORM mx         0         0
TUSSOCK ct         0         0
TUSSOCK mx         0         0

=====================================================================================================================================
OUTBREAKS by SERIES and YEAR
```

```
------------------------------------------------------------------------------------------------------------------------ CENTURY 1700
                    /--1700--\/--1710--\/--1720--\/--1730--\/--1740--\/--1750--\/--1760--\/--1770--\/--1780--\/--1790--\
Ident     S p a n   0123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123456789
good_r   1792 1983                                                                                              ........
good_r   1792 1983                                                                                              tttT....
CLING Mn 1792 1983                                                                                              ........
CLING Mn 1792 1983                                                                                              tttT....
------------------------------------------------------------------------------------------------------------------------ CENTURY 1800
                    /--1800--\/--1810--\/--1820--\/--1830--\/--1840--\/--1850--\/--1860--\/--1870--\/--1880--\/--1890--\
Ident     S p a n   0123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123456789
good_r   1792 1983  ..............bbbbbbBbbbbbbbbbbbbbbbbbbbbb...............................................................
good_r   1792 1983  .....................................................................................tttT...........
CLING Mn 1792 1983  ..............bbbbbbBbbbbbbbbbbbbbbbbbbbbb...............................................................
CLING Mn 1792 1983  .....................................................................................tttT...........
------------------------------------------------------------------------------------------------------------------------ CENTURY 1900
                    /--1900--\/--1910--\/--1920--\/--1930--\/--1940--\/--1950--\/--1960--\/--1970--\/--1980--\/--1990--\
Ident     S p a n   0123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123456789
good_r   1792 1983  .......................................................bbbbbbbbbbbbbB..bbbBbbbbbbbbbb
good_r   1792 1983  .......................................................................tttT.........
CLING Mn 1792 1983  .......................................................bbbbbbbbbbbbbB..bbbBbbbbbbbbbb
CLING Mn 1792 1983  .......................................................................tttT.........

============================================================================================================================= SUMMARY

AVERAGE OF OUTBREAKS BY INSECT
         No_of    Length   __Max_Growth_Reduction__  ___Growth_reduction____
Insect  outbreaks  years   Depart  CrIndex  Percent  Mean_periodic  Max_rate
------- --------- ------   ------  -------  -------  -------------  --------

BUDWORM
Average      6     18.33   -1.719     .604   37.58%      18.52%       1.44
Std dev      6      7.50     .039     .009     .85%       3.57%        .39
Minimum      6     13.00   -1.750     .598   36.49%      13.97%       1.13
Maximum      6     28.00   -1.669     .615   38.24%      21.41%       1.94

TUSSOCK
Average      6      4.00   -2.021     .538   44.18%      28.83%       1.17
Std dev      6       .00     .277     .061    6.06%       5.72%        .10
Minimum      6      4.00   -2.253     .487   36.49%      22.92%       1.04
Maximum      6      4.00   -1.669     .615   49.26%      35.62%       1.23

==================================================================================================================================
                                                        HISTOGRAMS

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        LENGTH OF OUTBREAK IN YEARS

Mid category   BUDWORM                                                                                      TUSSOCK

       5.158       0                                         |]]]]]]                                            6
```

7.567	0	|	0
9.977	0	|	0
12.386	2	[[|	0
14.795	2	[[|	0
17.205	0	|	0
19.614	0	|	0
22.023	0	|	0
24.433	0	|	0
26.842	2	[[|	0

MAX GROWTH REDUCTION, DEPARTURE

Mid category	BUDWORM		TUSSOCK
-2.225	0	|]]	2
-2.167	0	|]]	2
-2.108	0	|	0
-2.049	0	|	0
-1.991	0	|	0
-1.932	0	|	0
-1.873	0	|	0
-1.815	0	|	0
-1.756	4	[[[[|	0
-1.698	2	[[|]]	2

MAX GROWTH REDUCTION, CORRECTED INDEX

Mid category	BUDWORM		TUSSOCK
.494	0	|]]	2
.506	0	|]]	2
.519	0	|	0
.532	0	|	0
.545	0	|	0
.558	0	|	0
.570	0	|	0
.583	0	|	0
.596	4	[[[[|	0
.609	2	[[|]]	2

MAX GROWTH REDUCTION, PERCENT

Mid category	BUDWORM		TUSSOCK
37.106	2	[[|]]	2

```
       38.387       4                                       [[[[|                                             0
       39.669       0                                           |                                             0
       40.950       0                                           |                                             0
       42.232       0                                           |                                             0
       43.513       0                                           |                                             0
       44.795       0                                           |                                             0
       46.076       0                                           |                                             0
       47.358       0                                           |]]                                           2
       48.639       0                                           |]]                                           2

------------------------------------------------------------------------------------------------------------------------------------

         MEAN PERIODIC GROWTH REDUCTION

 Mid category   BUDWORM                                                                                  TUSSOCK

       15.011       2                                         [[|                                             0
       17.185       0                                           |                                             0
       19.359       2                                         [[|                                             0
       21.533       2                                         [[|                                             0
       23.707       0                                           |]]                                           2
       25.881       0                                           |                                             0
       28.056       0                                           |]]                                           2
       30.230       0                                           |                                             0
       32.404       0                                           |                                             0
       34.578       0                                           |]]                                           2

------------------------------------------------------------------------------------------------------------------------------------

         MAX RATE OF GROWTH REDUCTION

 Mid category   BUDWORM                                                                                  TUSSOCK

        1.087       2                                         [[|]]                                           2
        1.177       0                                           |                                             0
        1.267       2                                         [[|]]]]                                         4
        1.357       0                                           |                                             0
        1.447       0                                           |                                             0
        1.537       0                                           |                                             0
        1.627       0                                           |                                             0
        1.717       0                                           |                                             0
        1.808       0                                           |                                             0
        1.898       2                                         [[|                                             0

PROGRAM OUTBREAK - CORRECTED MEAN SERIES                                                           14:08  Thu 17 Jul 2014  Page   2
------------------------------------------------------------------------------------------------------------------------------------

 Non-host species control chronology:  nc002_crn.txt
 Tree indices from host species:       goodlinearstd.txt
 Title of run:
```

Corrected Mean Series

	Annual values										Number of samples									
Date	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
1792			732	698	638	507	912	1447	1057	1083			1	1	1	1	1	1	1	1
1800	1053	968	1085	932	1057	707	884	1037	1494	1736	1	1	1	1	1	1	1	1	1	1
1810	1323	899	876	1052	939	1179	985	895	807	737	1	1	1	1	1	1	1	1	1	1
1820	618	698	807	894	913	913	832	905	955	810	1	1	1	1	1	1	1	1	1	1
1830	735	786	968	656	672	749	716	942	929	1113	1	1	1	1	1	1	1	1	1	1
1840	948	990	1106	1130	1195	1144	1180	1042	940	967	1	1	1	1	1	1	1	1	1	1
1850	866	868	896	949	849	927	1279	1218	1241	1191	1	1	1	1	1	1	1	1	1	1
1860	1132	1147	1231	1152	973	1035	1094	1058	1137	1240	1	1	1	1	1	1	1	1	1	1
1870	1215	1065	1095	1096	940	946	1009	949	928	819	1	1	1	1	1	1	1	1	1	1
1880	933	995	1014	1094	1020	819	879	651	532	648	1	1	1	1	1	1	1	1	1	1
1890	666	1027	1108	1092	923	814	858	812	1025	1207	1	1	1	1	1	1	1	1	1	1
1900	1285	1274	1509	1335	1322	1179	1472	1217	1185	1009	1	1	1	1	1	1	1	1	1	1
1910	939	1183	1162	1115	1462	1289	1332	1073	997	896	1	1	1	1	1	1	1	1	1	1
1920	960	1006	932	887	1012	966	1022	1018	939	979	1	1	1	1	1	1	1	1	1	1
1930	1043	1013	883	975	946	947	999	1295	1320	1216	1	1	1	1	1	1	1	1	1	1
1940	1185	1392	1276	1162	1220	1237	1398	1351	1339	1361	1	1	1	1	1	1	1	1	1	1
1950	1278	1620	1279	1055	1056	900	828	664	667	873	1	1	1	1	1	1	1	1	1	1
1960	773	682	817	853	829	967	889	642	620	1048	1	1	1	1	1	1	1	1	1	1
1970	1138	868	827	753	635	638	722	712	653	778	1	1	1	1	1	1	1	1	1	1
1980	944	1099	937	809							1	1	1	1						

==

- = [OUTBREAK : CLINGOBR] = -

```
------------------------------------------------------------------------------------------------------------------------------------

 CONTROL CHRONOLOGY (non-host species):  LCRstd.txt
 HOST TREE indices or chronologies:      goodlinearstd.txt
 Title of run:

 Menu options:                                 Selected values
 -------------                                 ---------------
 Names of insects (Symbols)               BUDWORM (B,b)  TUSSOCK (T,t)

 Maximum growth reduction threshold
   1  BUDWORM                                    -1.28 Std Dev
   2  TUSSOCK                                    -1.28 Std Dev
 Minimum number of years for outbreak
   3  BUDWORM                                        8
         Outbreak omitted if it does not attain   8 years at end of series
   4  TUSSOCK                                        3
         Outbreak omitted if it does not attain   3 years at end of series
 Maximum years to count in outbreak
   5  TUSSOCK                                        4

   6  Rate of increase in growth reduction to
      identify TUSSOCK outbreaks                 1.000

   7  File made for plotting with Program PAGEPLOT:      N
      overlaying control chronology and uncorrected experimental series;
      and experimental series before and after correction

   8  File of negative corrected indices                 N


   9  Control chronology indices unchanged

 New files are:

      LECONOBR.OUT  For printing
      LECONOBR.COR  Tree indices corrected, Measurement format
      LECONOBR.MNC  Mean of corrected tree indices, Measurement format
      LECONOBR.NOR  Tree indices corrected and normalized, Compact format
      LECONOBR.DIF  Differences, uncorrected minus corrected series, Compact format
      LECONOBR.COL  Data in tab-delimited columns:  year, no of trees; count of outbreaks, percent of trees infested and maxima
                      for BUDWORM and TUSSOCK; corrected mean indices; corrected normalized indices
       and OBR.CRN  Mean chronology in publication format, appended

 Text in file: good -- no data title --                                  1st itrdb line missing
 Text in file: good -- no data title --                                  2nd itrdb line missing
 Text in file: good -- no data title --                                  3rd itrdb line missing
 Text in file: good -- no data title --                                  1st itrdb line missing
```

```
Text in file: good -- no data title --                                    2nd itrdb line missing
Text in file: good -- no data title --                                    3rd itrdb line missing

Control chronology:   good_r    1698  2013   316 years
Experimental series    1 trees  1792  2013   222 years
Analyzed time span              1792  2013   222 years
==================================================================================================================================
STATISTICS FOR CONTROL CHRONOLOGY AND EXPERIMENTAL SERIES BEFORE AND AFTER CORRECTION
Text in file: good -- no data title --                                    1st itrdb line missing
Text in file: good -- no data title --                                    2nd itrdb line missing
Text in file: good -- no data title --                                    3rd itrdb line missing

                                               Mean    Std   Skew- Kurto-  Trend   Partial autocorr  L-Box    Corr/  STATISTICS   1
Seq  Series      Interval  Years  Mean  Median  sens    dev   ness    sis  var %  Ord 1 Ord 2 Ord 3   Prob    Cntrl
---  --------  ---------- -----  ----- ------  -----  -----  ----- ------ ------- ----- ----- -----  -----    -----

     Control   1792  2013   222   .983   .968   .117   .196   .338  -.053   .0384   .70   .12  -.05   .000
  1  good_r    1792  2013   222   .978   .957   .126   .202   .702  1.584   .0509   .62   .02   .00   .000     .599
     Correct   1792  2013   222  1.000   .998   .095   .181   .517  4.233  -.0201   .67   .02  -.03   .000    -.448

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
MEAN SERIES                                    Mean    Std   Skew- Kurto-  Trend   Partial autocorr  L-Box    Corr/ STATISTICS MEAN
     Series      Interval  Years  Mean  Median  sens    dev   ness    sis  var %  Ord 1 Ord 2 Ord 3   Prob    Cntrl
     --------  ---------- -----  ----- ------  -----  -----  ----- ------ ------- ----- ----- -----  -----    -----
     Control   1792  2013   222   .983   .968   .117   .196   .338  -.053   .0384   .70   .12  -.05   .000    -.448
     TreeMean  1792  2013   222   .978   .957   .126   .202   .702  1.584   .0509   .62   .02   .00   .000     .599
     Correct   1792  2013   222  1.000   .998   .095   .181   .517  4.233  -.0201   .67   .02  -.03   .000    -.448

==================================================================================================================================
OUTBREAKS by SERIES
----------------------------------------------------------------------------------------------------------------------------------
TREE good_r    Span  1792  2013   222 years                                                                          SERIES   1
          Outbreak   No_of    _____Max_Growth_Reduction______    Mean_periodic   Max_rate_G.R.
Insect   time__span  Years    Year   Depart  CrIndex  Percent  growth_reduction  Year   Change
BUDWORM  1793  1807    15     1805   -3.753     .299   67.90%       22.62%       1798     2.25
BUDWORM  1825  1840    16     1838   -1.368     .730   24.76%       13.48%       1825     1.15
BUDWORM  1952  1969    18     1961   -1.823     .648   32.99%       17.82%       1952     1.53
TUSSOCK  1793  1796     4     1795   -2.342     .554   42.37%       20.04%       1795     1.69
TUSSOCK  1798  1801     4     1801   -1.960     .624   35.45%       13.02%       1798     2.25
TUSSOCK  1907  1910     4     1908   -1.782     .656   32.25%       22.56%       1908     1.77
TUSSOCK  1952  1955     4     1954   -1.694     .671   30.65%       21.32%       1952     1.53
--------------------------------
TREE good_r    OUTBREAKS by YEAR
Decade   0         1         2         3         4         5         6         7         8         9
    Year 0123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123456789

   1700                                                                                           .bbbbbbb
   1700                                                                                           .ttTt.tt
   1800  bbbbbBbb.................bbbbbbbbbbbbbBbb....................................................
   1800  tT..................................................................................................
   1900  ....................................................bbbbbbbbbBbbbbbbbb.............................
```

```
   1900  .......tTtt.........................................ttTt...........................................
   2000  ..............
   2000  ..............
------------------------------------------------------------------------------------------------------------------------------------
MEAN SERIES LECON Mn  Span  1792  2013   222 years                                                                      MEAN SERIES
          Outbreak   No_of    _____Max_Growth_Reduction______    Mean_periodic   Max_rate_G.R.
Insect   time__span  Years    Year   Depart  CrIndex  Percent  growth_reduction  Year   Change
BUDWORM  1793  1807    15     1805   -3.753     .299   67.90%        22.62%       1798     2.25
BUDWORM  1825  1840    16     1838   -1.368     .730   24.76%        13.48%       1825     1.15
BUDWORM  1952  1969    18     1961   -1.823     .648   32.99%        17.82%       1952     1.53
TUSSOCK  1793  1796     4     1795   -2.342     .554   42.37%        20.04%       1795     1.69
TUSSOCK  1798  1801     4     1801   -1.960     .624   35.45%        13.02%       1798     2.25
TUSSOCK  1907  1910     4     1908   -1.782     .656   32.25%        22.56%       1908     1.77
TUSSOCK  1952  1955     4     1954   -1.694     .671   30.65%        21.32%       1952     1.53
--------------------------------
TREE LECON Mn  OUTBREAKS by YEAR
Decade   0         1         2         3         4         5         6         7         8         9
    Year 0123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123456789

   1700                                                                                          .bbbbbbb
   1700                                                                                          .ttTt.tt
   1800  bbbbbBbb.................bbbbbbbbbbbbbBbb...............................................................
   1800  tT..................................................................................................
   1900  ...................................................bbbbbbbbbBbbbbbbbb..............................
   1900  .......tTtt.........................................ttTt...........................................
   2000  ..............
   2000  ..............

====================================================================================================================================

YEAR-BY-YEAR LIST of DEPARTURES (ST DEVS) and COUNTS
------------------------------------------------------------------------------------------------------------------------ DECADE 1792
    Ident       1792      1793      1794      1795      1796      1797      1798      1799      1800      1801
               -----     -----     -----     -----     -----     -----     -----     -----     -----     -----
    good_r       .80      -.21bt    -.65bt   -2.34bT   -1.22bt    1.98b     -.27bt    -.08bt    -.57bt   -1.96bT
    LECON Mn     .80      -.21bt    -.65bt   -2.34bT   -1.22bt    1.98b     -.27bt    -.08bt    -.57bt   -1.96bT

N of TREES         1         1         1         1         1         1         1         1         1         1
BUDWORM ct         0         1         1         1         1         1         1         1         1         1
BUDWORM mx         0         0         0         0         0         0         0         0         0         0
TUSSOCK ct         0         1         1         1         1         0         1         1         1         1
TUSSOCK mx         0         0         0         1         0         0         0         0         0         1
------------------------------------------------------------------------------------------------------------------------ DECADE 1802
    Ident       1802      1803      1804      1805      1806      1807      1808      1809      1810      1811
               -----     -----     -----     -----     -----     -----     -----     -----     -----     -----
    good_r     -2.11b    -2.30b    -1.98b    -3.75B    -2.34b     -.93b     2.20      3.48      1.04      -.06
    LECON Mn   -2.11b    -2.30b    -1.98b    -3.75B    -2.34b     -.93b     2.20      3.48      1.04      -.06

N of TREES         1         1         1         1         1         1         1         1         1         1
BUDWORM ct         1         1         1         1         1         1         0         0         0         0
BUDWORM mx         0         0         0         1         0         0         0         0         0         0
```

TUSSOCK ct	0	0	0	0	0	0	0	0	0	0
TUSSOCK mx	0	0	0	0	0	0	0	0	0	0

DECADE 1812

Ident	1812	1813	1814	1815	1816	1817	1818	1819	1820	1821
good_r	-.04	-.14	-.54	1.26	-.61	-.55	.19	-.57	-1.12	-1.01
LECON Mn	-.04	-.14	-.54	1.26	-.61	-.55	.19	-.57	-1.12	-1.01
N of TREES	1	1	1	1	1	1	1	1	1	1
BUDWORM ct	0	0	0	0	0	0	0	0	0	0
BUDWORM mx	0	0	0	0	0	0	0	0	0	0
TUSSOCK ct	0	0	0	0	0	0	0	0	0	0
TUSSOCK mx	0	0	0	0	0	0	0	0	0	0

DECADE 1822

Ident	1822	1823	1824	1825	1826	1827	1828	1829	1830	1831
good_r	-.88	.44	.48	-.66b	-1.14b	-.85b	-.38b	-.54b	-1.05b	-.37b
LECON Mn	-.88	.44	.48	-.66b	-1.14b	-.85b	-.38b	-.54b	-1.05b	-.37b
N of TREES	1	1	1	1	1	1	1	1	1	1
BUDWORM ct	0	0	0	1	1	1	1	1	1	1
BUDWORM mx	0	0	0	0	0	0	0	0	0	0
TUSSOCK ct	0	0	0	0	0	0	0	0	0	0
TUSSOCK mx	0	0	0	0	0	0	0	0	0	0

DECADE 1832

Ident	1832	1833	1834	1835	1836	1837	1838	1839	1840	1841
good_r	-.29b	-.79b	-1.14b	-1.03b	-1.10b	-.73b	-1.37B	-.06b	-.41b	.37
LECON Mn	-.29b	-.79b	-1.14b	-1.03b	-1.10b	-.73b	-1.37B	-.06b	-.41b	.37
N of TREES	1	1	1	1	1	1	1	1	1	1
BUDWORM ct	1	1	1	1	1	1	1	1	1	0
BUDWORM mx	0	0	0	0	0	0	1	0	0	0
TUSSOCK ct	0	0	0	0	0	0	0	0	0	0
TUSSOCK mx	0	0	0	0	0	0	0	0	0	0

DECADE 1842

Ident	1842	1843	1844	1845	1846	1847	1848	1849	1850	1851
good_r	.46	.71	.82	.58	1.36	.85	.49	.82	.51	.84
LECON Mn	.46	.71	.82	.58	1.36	.85	.49	.82	.51	.84
N of TREES	1	1	1	1	1	1	1	1	1	1
BUDWORM ct	0	0	0	0	0	0	0	0	0	0
BUDWORM mx	0	0	0	0	0	0	0	0	0	0
TUSSOCK ct	0	0	0	0	0	0	0	0	0	0
TUSSOCK mx	0	0	0	0	0	0	0	0	0	0

DECADE 1852

Ident	1852	1853	1854	1855	1856	1857	1858	1859	1860	1861
good_r	.73	.56	.59	.59	1.65	.87	.44	.59	.29	-.12
LECON Mn	.73	.56	.59	.59	1.65	.87	.44	.59	.29	-.12

N of TREES	1	1	1	1	1	1	1	1	1	1
BUDWORM ct	0	0	0	0	0	0	0	0	0	0
BUDWORM mx	0	0	0	0	0	0	0	0	0	0
TUSSOCK ct	0	0	0	0	0	0	0	0	0	0
TUSSOCK mx	0	0	0	0	0	0	0	0	0	0

DECADE 1862

Ident	1862	1863	1864	1865	1866	1867	1868	1869	1870	1871
good_r	.09	.51	.20	.25	.55	.56	-.17	.45	.92	.50
LECON Mn	.09	.51	.20	.25	.55	.56	-.17	.45	.92	.50
N of TREES	1	1	1	1	1	1	1	1	1	1
BUDWORM ct	0	0	0	0	0	0	0	0	0	0
BUDWORM mx	0	0	0	0	0	0	0	0	0	0
TUSSOCK ct	0	0	0	0	0	0	0	0	0	0
TUSSOCK mx	0	0	0	0	0	0	0	0	0	0

DECADE 1872

Ident	1872	1873	1874	1875	1876	1877	1878	1879	1880	1881
good_r	.60	.93	.31	.34	.58	-.01	-1.00	-.42	-.73	.15
LECON Mn	.60	.93	.31	.34	.58	-.01	-1.00	-.42	-.73	.15
N of TREES	1	1	1	1	1	1	1	1	1	1
BUDWORM ct	0	0	0	0	0	0	0	0	0	0
BUDWORM mx	0	0	0	0	0	0	0	0	0	0
TUSSOCK ct	0	0	0	0	0	0	0	0	0	0
TUSSOCK mx	0	0	0	0	0	0	0	0	0	0

DECADE 1882

Ident	1882	1883	1884	1885	1886	1887	1888	1889	1890	1891
good_r	-.17	.28	-.30	-.05	.07	-.29	-.51	-.52	-.39	-.43
LECON Mn	-.17	.28	-.30	-.05	.07	-.29	-.51	-.52	-.39	-.43
N of TREES	1	1	1	1	1	1	1	1	1	1
BUDWORM ct	0	0	0	0	0	0	0	0	0	0
BUDWORM mx	0	0	0	0	0	0	0	0	0	0
TUSSOCK ct	0	0	0	0	0	0	0	0	0	0
TUSSOCK mx	0	0	0	0	0	0	0	0	0	0

DECADE 1892

Ident	1892	1893	1894	1895	1896	1897	1898	1899	1900	1901
good_r	-1.25	-1.20	-.38	-.06	-.38	-.42	.26	1.02	.76	1.23
LECON Mn	-1.25	-1.20	-.38	-.06	-.38	-.42	.26	1.02	.76	1.23
N of TREES	1	1	1	1	1	1	1	1	1	1
BUDWORM ct	0	0	0	0	0	0	0	0	0	0
BUDWORM mx	0	0	0	0	0	0	0	0	0	0
TUSSOCK ct	0	0	0	0	0	0	0	0	0	0
TUSSOCK mx	0	0	0	0	0	0	0	0	0	0

DECADE 1902

```
    Ident       1902      1903      1904      1905      1906      1907      1908      1909      1910      1911
               -----     -----     -----     -----     -----     -----     -----     -----     -----     -----
    good_r      1.35       .70      1.04       .24      1.02      -.01 t   -1.78 T   -1.61 t   -1.58 t    -.47
    LECON Mn    1.35       .70      1.04       .24      1.02      -.01 t   -1.78 T   -1.61 t   -1.58 t    -.47

N of TREES         1         1         1         1         1         1         1         1         1         1
BUDWORM ct         0         0         0         0         0         0         0         0         0         0
BUDWORM mx         0         0         0         0         0         0         0         0         0         0
TUSSOCK ct         0         0         0         0         0         1         1         1         1         0
TUSSOCK mx         0         0         0         0         0         0         1         0         0         0
------------------------------------------------------------------------------------------------------------------------ DECADE 1912
    Ident       1912      1913      1914      1915      1916      1917      1918      1919      1920      1921
               -----     -----     -----     -----     -----     -----     -----     -----     -----     -----
    good_r      -.66      -.18       .96       .70      1.54      1.03       .59       .09       .14      -.42
    LECON Mn    -.66      -.18       .96       .70      1.54      1.03       .59       .09       .14      -.42

N of TREES         1         1         1         1         1         1         1         1         1         1
BUDWORM ct         0         0         0         0         0         0         0         0         0         0
BUDWORM mx         0         0         0         0         0         0         0         0         0         0
TUSSOCK ct         0         0         0         0         0         0         0         0         0         0
TUSSOCK mx         0         0         0         0         0         0         0         0         0         0
------------------------------------------------------------------------------------------------------------------------ DECADE 1922
    Ident       1922      1923      1924      1925      1926      1927      1928      1929      1930      1931
               -----     -----     -----     -----     -----     -----     -----     -----     -----     -----
    good_r      -.11      -.19      -.48      -.24      -.35      -.22       .31       .29       .67      -.10
    LECON Mn    -.11      -.19      -.48      -.24      -.35      -.22       .31       .29       .67      -.10

N of TREES         1         1         1         1         1         1         1         1         1         1
BUDWORM ct         0         0         0         0         0         0         0         0         0         0
BUDWORM mx         0         0         0         0         0         0         0         0         0         0
TUSSOCK ct         0         0         0         0         0         0         0         0         0         0
TUSSOCK mx         0         0         0         0         0         0         0         0         0         0
------------------------------------------------------------------------------------------------------------------------ DECADE 1932
    Ident       1932      1933      1934      1935      1936      1937      1938      1939      1940      1941
               -----     -----     -----     -----     -----     -----     -----     -----     -----     -----
    good_r       .12       .58      -.25      -.78      -.70      -.26       .12       .04      -.17      -.12
    LECON Mn     .12       .58      -.25      -.78      -.70      -.26       .12       .04      -.17      -.12

N of TREES         1         1         1         1         1         1         1         1         1         1
BUDWORM ct         0         0         0         0         0         0         0         0         0         0
BUDWORM mx         0         0         0         0         0         0         0         0         0         0
TUSSOCK ct         0         0         0         0         0         0         0         0         0         0
TUSSOCK mx         0         0         0         0         0         0         0         0         0         0
------------------------------------------------------------------------------------------------------------------------ DECADE 1942
    Ident       1942      1943      1944      1945      1946      1947      1948      1949      1950      1951
               -----     -----     -----     -----     -----     -----     -----     -----     -----     -----
    good_r      -.01      -.15       .60       .04      -.20       .56      1.06      1.10       .65       .97
    LECON Mn    -.01      -.15       .60       .04      -.20       .56      1.06      1.10       .65       .97

N of TREES         1         1         1         1         1         1         1         1         1         1
BUDWORM ct         0         0         0         0         0         0         0         0         0         0
```

```
BUDWORM mx        0         0         0         0         0         0         0         0         0         0
TUSSOCK ct        0         0         0         0         0         0         0         0         0         0
TUSSOCK mx        0         0         0         0         0         0         0         0         0         0
------------------------------------------------------------------------------------------------------------------------ DECADE 1952
    Ident       1952      1953      1954      1955      1956      1957      1958      1959      1960      1961
               -----     -----     -----     -----     -----     -----     -----     -----     -----     -----
    good_r      -.56bt   -1.16bt   -1.69bT   -1.30bt   -1.59b    -1.58b    -1.32b    -1.60b    -1.00b    -1.82B
    LECON Mn    -.56bt   -1.16bt   -1.69bT   -1.30bt   -1.59b    -1.58b    -1.32b    -1.60b    -1.00b    -1.82B

N of TREES        1         1         1         1         1         1         1         1         1         1
BUDWORM ct        1         1         1         1         1         1         1         1         1         1
BUDWORM mx        0         0         0         0         0         0         0         0         0         1
TUSSOCK ct        1         1         1         1         0         0         0         0         0         0
TUSSOCK mx        0         0         1         0         0         0         0         0         0         0
------------------------------------------------------------------------------------------------------------------------ DECADE 1962
    Ident       1962      1963      1964      1965      1966      1967      1968      1969      1970      1971
               -----     -----     -----     -----     -----     -----     -----     -----     -----     -----
    good_r     -1.54b    -1.19b     -.08b     -.10b     -.04b     -.31b     -.66b     -.18b       .16       .44
    LECON Mn   -1.54b    -1.19b     -.08b     -.10b     -.04b     -.31b     -.66b     -.18b       .16       .44

N of TREES        1         1         1         1         1         1         1         1         1         1
BUDWORM ct        1         1         1         1         1         1         1         1         0         0
BUDWORM mx        0         0         0         0         0         0         0         0         0         0
TUSSOCK ct        0         0         0         0         0         0         0         0         0         0
TUSSOCK mx        0         0         0         0         0         0         0         0         0         0
------------------------------------------------------------------------------------------------------------------------ DECADE 1972
    Ident       1972      1973      1974      1975      1976      1977      1978      1979      1980      1981
               -----     -----     -----     -----     -----     -----     -----     -----     -----     -----
    good_r       .35       .64       .19       .06       .12       .48       .10       .13      -.01       .38
    LECON Mn     .35       .64       .19       .06       .12       .48       .10       .13      -.01       .38

N of TREES        1         1         1         1         1         1         1         1         1         1
BUDWORM ct        0         0         0         0         0         0         0         0         0         0
BUDWORM mx        0         0         0         0         0         0         0         0         0         0
TUSSOCK ct        0         0         0         0         0         0         0         0         0         0
TUSSOCK mx        0         0         0         0         0         0         0         0         0         0
------------------------------------------------------------------------------------------------------------------------ DECADE 1982
    Ident       1982      1983      1984      1985      1986      1987      1988      1989      1990      1991
               -----     -----     -----     -----     -----     -----     -----     -----     -----     -----
    good_r       .03      -.72      -.40      -.74      -.01       .81       .54       .41       .13      1.11
    LECON Mn     .03      -.72      -.40      -.74      -.01       .81       .54       .41       .13      1.11

N of TREES        1         1         1         1         1         1         1         1         1         1
BUDWORM ct        0         0         0         0         0         0         0         0         0         0
BUDWORM mx        0         0         0         0         0         0         0         0         0         0
TUSSOCK ct        0         0         0         0         0         0         0         0         0         0
TUSSOCK mx        0         0         0         0         0         0         0         0         0         0
------------------------------------------------------------------------------------------------------------------------ DECADE 1992
    Ident       1992      1993      1994      1995      1996      1997      1998      1999      2000      2001
               -----     -----     -----     -----     -----     -----     -----     -----     -----     -----
    good_r       .57       .89       .42      -.27       .70       .28       .06      -.27      -.41      -.19
```

```
    LECON Mn     .57       .89       .42      -.27       .70       .28       .06      -.27      -.41      -.19

N of TREES         1         1         1         1         1         1         1         1         1         1
BUDWORM ct         0         0         0         0         0         0         0         0         0         0
BUDWORM mx         0         0         0         0         0         0         0         0         0         0
TUSSOCK ct         0         0         0         0         0         0         0         0         0         0
TUSSOCK mx         0         0         0         0         0         0         0         0         0         0
----------------------------------------------------------------------------------------------------------------------- DECADE 2002
    Ident       2002      2003      2004      2005      2006      2007      2008      2009      2010      2011
               -----     -----     -----     -----     -----     -----     -----     -----     -----     -----

    good_r      -.20      -.03      -.53      -.41       .96      1.07      1.55      1.79      2.57      2.56
    LECON Mn    -.20      -.03      -.53      -.41       .96      1.07      1.55      1.79      2.57      2.56

N of TREES         1         1         1         1         1         1         1         1         1         1
BUDWORM ct         0         0         0         0         0         0         0         0         0         0
BUDWORM mx         0         0         0         0         0         0         0         0         0         0
TUSSOCK ct         0         0         0         0         0         0         0         0         0         0
TUSSOCK mx         0         0         0         0         0         0         0         0         0         0
----------------------------------------------------------------------------------------------------------------------- DECADE 2012
    Ident       2012      2013
               -----     -----     -----     -----     -----     -----     -----     -----     -----     -----

    good_r      2.09      5.25
    LECON Mn    2.09      5.25

N of TREES         1         1
BUDWORM ct         0         0
BUDWORM mx         0         0
TUSSOCK ct         0         0
TUSSOCK mx         0         0

===================================================================================================================================
OUTBREAKS by SERIES and YEAR
---------------------------------------------------------------------------------------------------------------------- CENTURY 1700
                    /--1700--\/--1710--\/--1720--\/--1730--\/--1740--\/--1750--\/--1760--\/--1770--\/--1780--\/--1790--\
Ident     S p a n   0123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123456789
good_r   1792 2013                                                                                              .bbbbbbb
good_r   1792 2013                                                                                              .ttTt.tt
LECON Mn 1792 2013                                                                                              .bbbbbbb
LECON Mn 1792 2013                                                                                              .ttTt.tt
---------------------------------------------------------------------------------------------------------------------- CENTURY 1800
                    /--1800--\/--1810--\/--1820--\/--1830--\/--1840--\/--1850--\/--1860--\/--1870--\/--1880--\/--1890--\
Ident     S p a n   0123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123456789
good_r   1792 2013  bbbbbBbb.................bbbbbbbbbbbbbBbb...........................................................
good_r   1792 2013  tT..................................................................................................
LECON Mn 1792 2013  bbbbbBbb.................bbbbbbbbbbbbbBbb...........................................................
LECON Mn 1792 2013  tT..................................................................................................
---------------------------------------------------------------------------------------------------------------------- CENTURY 1900
                    /--1900--\/--1910--\/--1920--\/--1930--\/--1940--\/--1950--\/--1960--\/--1970--\/--1980--\/--1990--\
Ident     S p a n   0123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123456789
good_r   1792 2013  ....................................................bbbbbbbbbBbbbbbbbb..............................
good_r   1792 2013  .......tTtt.........................................ttTt............................................
```

```
LECON Mn 1792 2013  ....................................................bbbbbbbbbBbbbbbbbbb.............................
LECON Mn 1792 2013  .......tTtt.....................................ttTt.........................................
------------------------------------------------------------------------------------------------------------------------ CENTURY 2000
                    /--2000--\/--2010--\/--2020--\/--2030--\/--2040--\/--2050--\/--2060--\/--2070--\/--2080--\/--2090--\
Ident     S p a n   0123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123456789
good_r   1792 2013  .............
good_r   1792 2013  .............
LECON Mn 1792 2013  .............
LECON Mn 1792 2013  .............

============================================================================================================================= SUMMARY

AVERAGE OF OUTBREAKS BY INSECT
          No_of    Length    __Max_Growth_Reduction__  ___Growth_reduction____
Insect  outbreaks   years    Depart  CrIndex  Percent  Mean_periodic  Max_rate
------- ---------  ------    ------  -------  -------  -------------  --------

BUDWORM
Average      6      16.33   -2.315     .559   41.88%      17.97%       1.64
Std dev      6       1.37    1.132     .205   20.49%       4.09%        .50
Minimum      6      15.00   -3.753     .299   24.76%      13.48%       1.15
Maximum      6      18.00   -1.368     .730   67.90%      22.62%       2.25

TUSSOCK
Average      8       4.00   -1.945     .626   35.18%      19.24%       1.81
Std dev      8        .00     .266     .048    4.81%       3.95%        .29
Minimum      8       4.00   -2.342     .554   30.65%      13.02%       1.53
Maximum      8       4.00   -1.694     .671   42.37%      22.56%       2.25

=====================================================================================================================================
                                                            HISTOGRAMS

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        LENGTH OF OUTBREAK IN YEARS

Mid category   BUDWORM                                                                                          TUSSOCK

      4.675       0                                        |]]]]]]]]                                              8
      6.081       0                                        |                                                      0
      7.486       0                                        |                                                      0
      8.892       0                                        |                                                      0
     10.297       0                                        |                                                      0
     11.703       0                                        |                                                      0
     13.108       0                                        |                                                      0
     14.514       2                                      [[|                                                      0
     15.919       2                                      [[|                                                      0
     17.325       2                                      [[|                                                      0

--------------------------------------------------------------------------------------------------------------------------------------
```

```
        MAX GROWTH REDUCTION, DEPARTURE

Mid category   BUDWORM                                                                    TUSSOCK

     -3.638       2                          [[|                                             0
     -3.399       0                            |                                             0
     -3.159       0                            |                                             0
     -2.920       0                            |                                             0
     -2.680       0                            |                                             0
     -2.441       0                            |]]                                           2
     -2.202       0                            |                                             0
     -1.962       0                            |]]                                           2
     -1.723       2                          [[|]]]]                                         4
     -1.483       2                          [[|                                             0

-----------------------------------------------------------------------------------------------------

        MAX GROWTH REDUCTION, CORRECTED INDEX

Mid category   BUDWORM                                                                    TUSSOCK

       .320       2                          [[|                                             0
       .363       0                            |                                             0
       .406       0                            |                                             0
       .450       0                            |                                             0
       .493       0                            |                                             0
       .536       0                            |]]                                           2
       .580       0                            |                                             0
       .623       0                            |]]                                           2
       .666       2                          [[|]]]]                                         4
       .710       2                          [[|                                             0

-----------------------------------------------------------------------------------------------------

        MAX GROWTH REDUCTION, PERCENT

Mid category   BUDWORM                                                                    TUSSOCK

     26.838       2                          [[|                                             0
     31.169       2                          [[|]]]]                                         4
     35.500       0                            |]]                                           2
     39.831       0                            |                                             0
     44.162       0                            |]]                                           2
     48.493       0                            |                                             0
     52.824       0                            |                                             0
     57.155       0                            |                                             0
     61.486       0                            |                                             0
     65.817       2                          [[|                                             0

-----------------------------------------------------------------------------------------------------
```

```
        MEAN PERIODIC GROWTH REDUCTION

Mid category   BUDWORM                                                                   TUSSOCK

      13.480       2                                    [[|]]                                     2
      14.444       0                                      |                                       0
      15.408       0                                      |                                       0
      16.371       0                                      |                                       0
      17.335       0                                      |                                       0
      18.299       2                                    [[|                                       0
      19.263       0                                      |                                       0
      20.226       0                                      |]]                                     2
      21.190       0                                      |]]                                     2
      22.154       2                                    [[|]]                                     2

-----------------------------------------------------------------------------------------------------------------------------------

        MAX RATE OF GROWTH REDUCTION

Mid category   BUDWORM                                                                   TUSSOCK

       1.202       2                                    [[|                                       0
       1.312       0                                      |                                       0
       1.423       0                                      |                                       0
       1.534       2                                    [[|]]                                     2
       1.645       0                                      |]]                                     2
       1.755       0                                      |]]                                     2
       1.866       0                                      |                                       0
       1.977       0                                      |                                       0
       2.087       0                                      |                                       0
       2.198       2                                    [[|]]                                     2
```

Non-host species control chronology: LCRstd.txt
Tree indices from host species: goodlinearstd.txt
Title of run:

Corrected Mean Series

	Annual values										Number of samples									
Date	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
1792			1145	961	882	576	779	1358	951	986			1	1	1	1	1	1	1	1
1800	897	645	618	584	642	321	577	831	1397	1630	1	1	1	1	1	1	1	1	1	1
1810	1189	989	993	975	902	1227	890	901	1034	897	1	1	1	1	1	1	1	1	1	1
1820	798	818	840	1079	1088	880	794	847	931	902	1	1	1	1	1	1	1	1	1	1
1830	810	932	947	858	794	814	801	868	752	989	1	1	1	1	1	1	1	1	1	1
1840	926	1067	1083	1128	1149	1104	1246	1154	1089	1148	1	1	1	1	1	1	1	1	1	1
1850	1093	1152	1131	1101	1106	1106	1298	1158	1080	1107	1	1	1	1	1	1	1	1	1	1
1860	1052	978	1017	1092	1037	1045	1100	1101	969	1081	1	1	1	1	1	1	1	1	1	1
1870	1167	1090	1108	1168	1056	1061	1105	998	818	925	1	1	1	1	1	1	1	1	1	1
1880	867	1028	970	1050	946	991	1012	947	907	906	1	1	1	1	1	1	1	1	1	1
1890	929	923	774	783	931	990	932	924	1046	1185	1	1	1	1	1	1	1	1	1	1
1900	1138	1223	1244	1127	1187	1043	1185	998	678	709	1	1	1	1	1	1	1	1	1	1
1910	714	916	880	968	1174	1127	1279	1186	1107	1017	1	1	1	1	1	1	1	1	1	1
1920	1025	925	980	966	912	957	936	961	1057	1053	1	1	1	1	1	1	1	1	1	1
1930	1121	982	1022	1104	955	859	874	952	1021	1007	1	1	1	1	1	1	1	1	1	1
1940	970	977	998	973	1109	1007	963	1101	1192	1199	1	1	1	1	1	1	1	1	1	1
1950	1118	1176	899	791	693	764	713	713	761	711	1	1	1	1	1	1	1	1	1	1
1960	819	670	721	785	986	982	992	943	880	967	1	1	1	1	1	1	1	1	1	1
1970	1028	1079	1063	1116	1035	1010	1022	1087	1018	1023	1	1	1	1	1	1	1	1	1	1
1980	998	1070	1006	870	928	867	999	1147	1098	1075	1	1	1	1	1	1	1	1	1	1
1990	1023	1201	1104	1161	1077	951	1126	1051	1011	952	1	1	1	1	1	1	1	1	1	1
2000	927	966	963	994	905	926	1173	1194	1281	1324	1	1	1	1	1	1	1	1	1	1
2010	1465	1464	1378	1949							1	1	1	1						

- = [OUTBREAK : LECONOBR] = -

Appendix 6. Locations for All Sampled Trees

Tree ID	Lat LongN/W
tree core LC01-1A	35.6511111 -083.4413056
tree core LC01-2A	35.6510278 -083.4412778
tree core LC01-3A	35.6509722 -083.4413333
tree core LC01-4A	35.6510556 -083.4413333
tree core LC01-5A	35.6511389 -083.4413056
tree core LC01-6	35.6512778 -083.4413333
tree core LC01-7	35.6510833 -083.4412778
tree core LC01-8A	35.6508333 -083.4403889
tree core LC01-9A	35.6508611 -083.4405556
tree core LC01-10A	35.6508333 -083.4406111
tree core LC01-11A	35.6509167 -083.4406389
tree core LC01-12A	35.6509167 -083.4406389
tree core LC01-13A	35.6509167 -083.4406389
tree core LC01-14	35.6508611 -083.4405556
tree core LC01-15A	35.6508611 -083.4405556
tree core LC01-16A	35.6508889 -083.4406944
tree core LC01-17	35.6508611 -083.4406389
tree core LC01-18A	35.6509444 -083.4405000
tree core LC01-19A	35.6508333 -083.4405278
tree core LC01-20	35.6508333 -083.4405833
tree core LC01-21A	35.6508056 -083.4405833
tree core LC01-22A	35.6507222 -083.4405833
tree core LC01-23	35.6507500 -083.4404722
tree core LC01-24A	35.6506944 -083.4405278
tree core LC01-25A	35.6506944 -083.4405556
tree core LC01-26A	35.6509167 -083.4403333
tree core LC01-28A	35.6506111 -083.4405000
tree core LC01-29A	35.6506389 -083.4405000
tree core LC01-30A	35.6506667 -083.4405000
tree core LC01-31A	35.6506389 -083.4405833
tree core LC01-32A	35.6505000 -083.4407222
tree core LC01-33A	35.6504444 -083.4405278
tree core LC01-34	35.6505556 -083.4406389
tree core LC01-35A	35.6508611 -083.4408889
tree core LC01-36A	35.6508889 -083.4408611
tree core LC01-37A	35.6509722 -083.4470222
tree core LC01-38A	35.6510556 -083.4402778
tree core LC01-39B	35.6512500 -083.4408056
tree core LC01-40A	35.6513056 -083.4408889
tree core BV02-1A	35.6541944 -083.4304444

tree core BV02-2A	35.6551111 -083.4302778
tree core BV02-3A	35.6542778 -083.4303333
tree core BV02-4A	35.6536889 -083.4305306
tree core BV02-5A	35.6537667 -083.4300278
tree core BV02-6A	35.6535000 -083.4303056
tree core SB8-1A	35.6511389 -083.4356667
tree core SB8-2A	35.6514722 -083.4359167
tree core SB8-3	35.6506944 -083.4351944
tree core SB8-4	35.6509167 -083.4356944
tree core LCR-1	35.65525 -083.4453333
tree core LCR-2	35.65554722 -083.4452778
tree core LCR-3	35.5554722 -083.44552778
tree core LCR-4	35.631111 -083.4443889
tree core LCR-5	35.6528333 -083.444444
tree core LCR-6	35.6524167 -083.4445000
tree core LCR-7	35.6522778 -083.4443333
tree core LCR-8	35.6512778 -083.4447778
tree core LCR-9	35.6510278 083.4441667
tree core LCR-10	35.6511944 -083.4440000
tree core LCR-11	35.64285 -083.44276
tree core LCR-12	35.64279 -083.44279
tree core LCR-13	35.65091 -083.44424
tree core LCR-14	35.65118 -083.44373
tree core LCR-15	35.65123 -083.44373
tree core LCR-16	35.65131 -083.44336
tree core LCR-17	35.65140 -083.44337
tree core LCR-18	35.65147 -083.44321
tree core LCR-19	35.65136 -083.44312
tree core LCR-20	35.65046 -083.43993
tree core LCR-21	35.65047 -083.43998
tree core LCR-22	35.65011 -083.43955
tree core LCR-23	35.65020 -083.43927
tree core LCR-24	35.65011 -083.43918
tree core LCR-25	35.64980 -083.43819
tree core LCR-26	35.65063 -083.43679
tree core LCR-27	35.65081 -083.43629
tree core LCR-28	35.65049 -083.43627
tree core LCR-29	35.65024 -083.43652
tree core LCR-30	35.64949 -083.43681
tree core LCR-31	35.64820 -083.43743

VITA

Maegen Rochner was born in Louisville, Kentucky and raised in Corydon, Indiana as the eldest of two children. She graduated from Corydon Central High School in 2005, and earned an Associate of Applied Science degree in Culinary Arts from Robert Morris College Chicago in 2006, as well as two Bachelor of Arts degrees, one in English/Writing and another in Geology from Indiana University Southeast in 2010. Her interest in dendrochronology was sparked when she toured the University of Tennessee Knoxville and found a way that she could pursue a Master of Science degree combining her love of geology with a newfound love of dendrochronology. She chose to continue her education in Physical Geography at the University of Tennessee, focusing on dendrochronology and geomorphology. While a student at UT, she worked as a Graduate Teaching Assistant for introductory courses on physical geography all four of her M.S. semesters. Maegen will be continuing her education as a PhD student in Geography at the University of Tennessee, studying under Dr. Henri D. Grissino-Mayer.